NEHRP External Grant Award 02HQGR0102

QUATERNARY FAULTING IN THE WILLIAMS FORK VALLEY GRABEN, NORTH-CENTRAL COLORADO, AND COMPARISON WITH LATE QUATERNARY DEFORMATION NEAR SPINNEY MOUNTAIN, CENTRAL COLORADO

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ABSTRACT

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The Williams Fork Valley graben is a wedge-shaped, late Cenozoic structure in north-central Colorado. The graben formed in the hanging wall of the pre-existing Laramide Williams Range thrust. Strong evidence of late Quaternary deformation, primarily tectonic scarps in surficial deposits, is present along most of the 18-km-long northern section of the Williams Fork Mountains fault, an east-dipping normal fault that bounds the western margin of the graben. No conclusive evidence of Quaternary activity was discovered on the 18-km-long southern section of the Williams Fork Mountains fault or on faults that form the eastern margin of the graben. However, the southern section of the Williams Fork Mountains fault lies within Proterozoic rocks along much of its length, and seldom crosses late Quaternary deposits.

Because the forest cover is dense and the valleys are very narrow along the northern section of the Williams Fork Mountains fault, it is difficult to discern on aerial photography whether topographic scarps exist in the young valley-fill deposits along the fault trace. Since the aerial photography is of limited use, we conducted foot traverses to search for tectonic scarps in young deposits. Prominent scarps are present in all of the valleys, but some scarps are suspected to be of non-tectonic origin. To distinguish tectonic scarps from non-tectonic ones, the fault was first located in bedrock on the interfluves, and then traced along the fault-line scarp to the valley floor. Scarps that coincided with the fault-line scarp were interpreted as tectonic features unless other evidence supported a non-tectonic origin for the scarp.

Geologic sketch maps were prepared for eleven sites with late Quaternary scarps along the Williams Fork Mountains fault. Nineteen topographic profiles were measured across the scarps at these sites to estimate scarp height, surface offset, and maximum scarp angle. Existing exposures of the faulted surficial deposits were rare, therefore six soil pits were excavated into faulted deposits at four of the sites. The soils data from the pits were used in conjunction with other relative age data to estimate the ages of faulted deposits. Evidence of Holocene fault rupture was documented at a few of the sites. Most estimated slip rates ranged from 0.1-0.3 mm/year.

Middle and possibly early Pleistocene alluvium caps several mesas within the interior of the graben. These deposits are displaced and tilted by Quaternary faults that strike obliquely across the graben, creating a series of northeast-trending tilted fault blocks or half grabens. Tributary streams flowing across these blocks follow the base of the fault scarps. Fluvial deposition and erosion along the scarps has altered the tectonic geomorphology of these Quaternary faults.

The original proposal was not fully funded. On the basis of the recommendation of the proposal review panel, the comparative analysis with late Quaternary deformation near Spinney Mountain was removed from the scope of work.

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INTRODUCTION

The Colorado Geological Survey (CGS) investigated the neotectonic history of the Williams Fork Valley graben in north-central Colorado (Fig. 1) as part of a study funded by the U.S. Geological Survey (USGS) through the National Earthquake Hazard Reduction Program (NEHRP). This area was selected for study chiefly on the basis of the reported Holocene faulting that was described by Unruh and others (1993, 1996) at a single location on one of the graben-bounding faults. As originally proposed, the study was to focus on Quaternary faulting associated with the graben and determine if Holocene rupture occurred at locations other than the one described by Unruh and others (1993, 1996). Estimation of slip rates on young faults was another emphasis of the study, as was a comparison of the evidence of recent faulting in the graben to late Quaternary deformation near Spinney Mountain in South Park (Fig. 1). Unfortunately, the original proposal was not fully funded. Following the recommendation of the proposal review panel, the comparative analysis with the Spinney Mountain area was removed from the scope of work.

Relevant geographic features in and near the project area are shown in Figure 2. The project area lies between the Vasquez Mountains on the east, which are an element of the much larger Front Range, and the Williams Fork Mountains on the west. The southern end of the project area is about six kilometers (km) southeast of Ute Park, and the northern end extends nearly to Williams Fork Reservoir.

During the initial reconnaissance phase of the investigation, existing geologic mapping by Tweto (1973, 1976), Tweto and Reed (1973), Tweto and others (1978), Ellis (1976), Kirkham and Rogers, (1981), and Unruh and others (1993, 1996) was examined. Compilations of existing information on Quaternary faulting (Widmann and others, 1998) and late Cenozoic faulting (Widmann and others, 2002) were also evaluated. Several Neogene faults exist in the region, but Quaternary activity has been documented or proposed only on a limited number of the faults (Widmann and others, 2002). Unruh and others (1993, 1996) described strong evidence of Holocene movement at a single location along one of the graben-bounding faults.

A variety of aerial photography that either cover all or parts of the project area were viewed and interpreted. They included 1:40,000-scale black and white photography flown in 1999, 1:24,000-scale natural color photography flown in 1981, 1:16,000-scale natural color photography flown in 2000, and 1:20,000-scale black and white photography flown in1938. Landsat imagery and oblique and vertical shaded relief images generated from 30-meter (m) digital elevation models (DEMs) were also utilized.

During the initial phase of the study, geomorphic features indicative of recent tectonism were noted on aerial photography, LANDSAT imagery, and shaded relief DEMS along the northern section of the Williams Fork Mountains fault, which forms the western margin of the Williams Fork Valley graben. Geomorphic evidence observed on aerial photography also suggested several of the cross faults within the interior of the graben were active during the

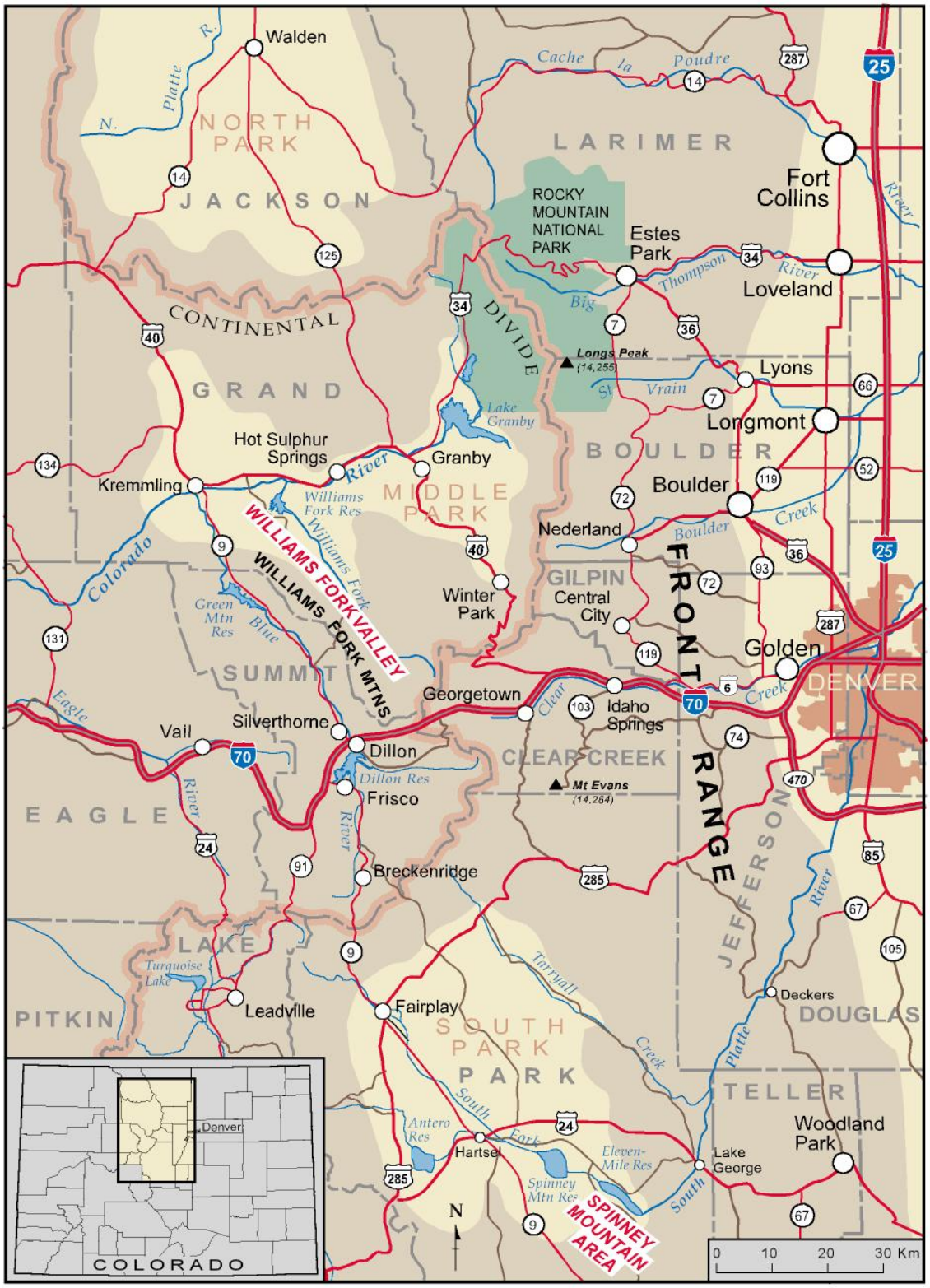

Figure 1. Regional location map.

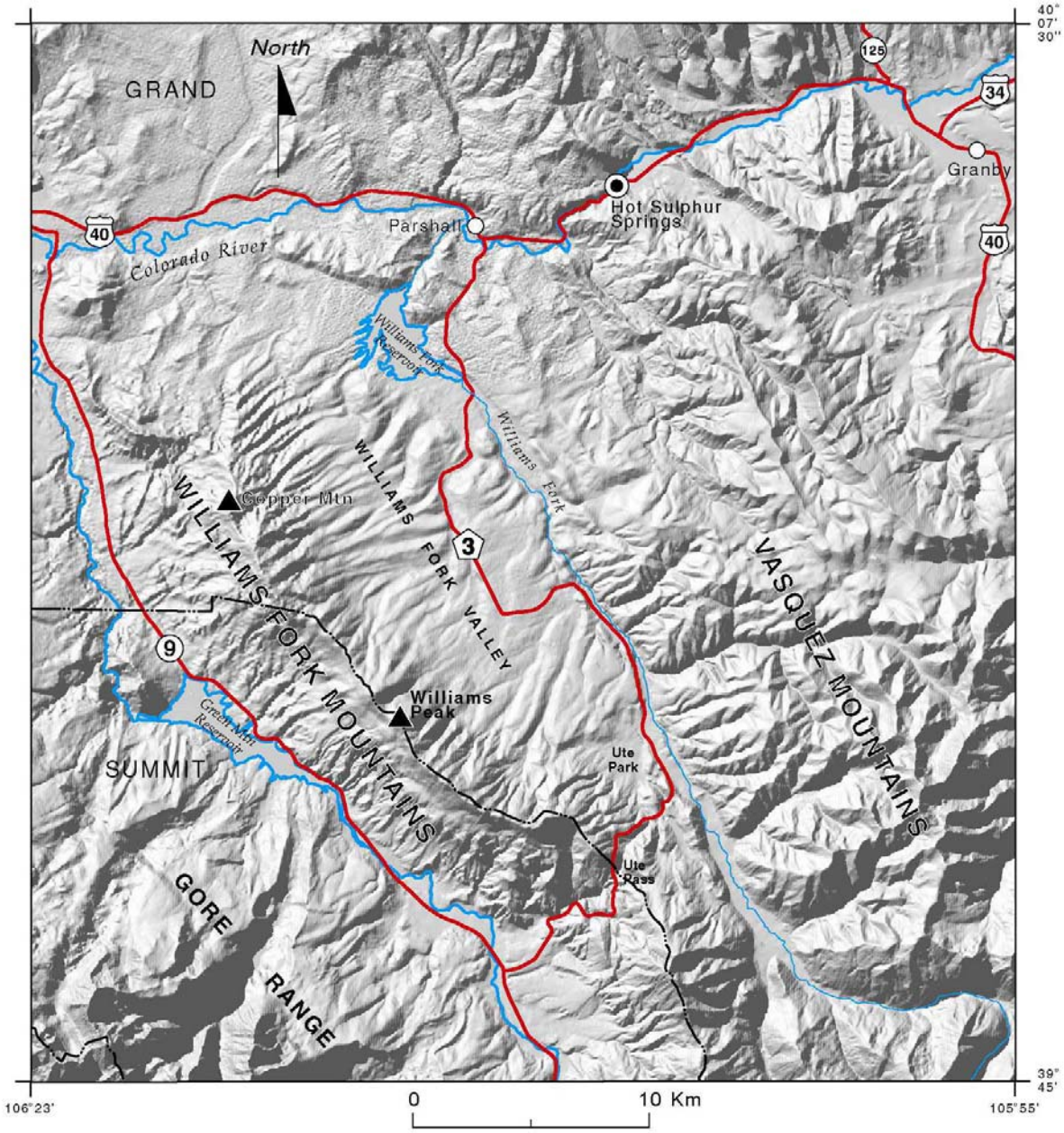

Figure 2. Project area map (base map is shaded-relief image created from 30-m DEM).

Quaternary. Compelling evidence of late Quaternary tectonism was not detected on the aerial photography that covers the southern section of the fault or along the faults that bound the east side of the graben. These observations prompted the investigation to focus on the northern section of the Williams Fork Mountains fault. Limited field studies were conducted along the southern end of the fault and along the faults that form the east margin of the graben to confirm the absence of evidence for late Quaternary faulting. Only brief field investigations were conducted on the cross faults within the interior of the graben. These relatively short faults may rupture coseismically with the Williams Fork Mountains fault, and they may be too short in length to be included in the fault database for the USGS national seismic hazard maps.

Our original project plan involved the extensive use of aerial photography to select four or five sites worthy of detailed study. Much of the project time could then be spent thoroughly examining the selected sites. Due to dense forest cover, the aerial photography was of limited use to identify and evaluate scarps in young surficial deposits along the northern section of the Williams Fork Mountains fault. Therefore, time-consuming foot traverses were made along this part of the fault. Although this effort resulted in the discovery of numerous sites with fault scarps in late Quaternary deposits, which supported our major goal of documenting the recent tectonic history of the fault, it did reduce the amount of time available for detailed evaluation of the favorable sites.

Eleven sites were selected for more thorough study based on the foot traverses. Reconnaissance-level geologic sketch maps were prepared in the field for each of the eleven sites. These sketch maps depict the surficial deposits at the sites and the presence or absence of fault scarps in Quaternary deposits. No attempt was made to map out different Proterozoic rock units. At some sites, the major surficial units are split into subunits on the basis of their relative ages (e.g. at Middle Mule Creek site, unit Qa1 is divided into units Qa1a and Qa1b). The subunits may or may not correlate with similarly named subunits at other sites (e.g. unit Qa1a at the Middle Mule Creek site may or may not correlate with unit Qa1a at the Southern Battle Creek site).

The dense forest cover and lack of adequate published topographic base maps complicated the preparation of the geologic sketch maps. UTM coordinates were acquired for many data points using a hand-held GPS unit, but the dense forest cover also reduced the accuracy of the GPS readings. ERDAS photogrammetric software was used to create properly oriented sketch maps with fairly accurate scales. Geologic data collected in the field was drafted on aerial photographs. The photographs were subsequently scanned, georeferenced, and used with ERDAS software to develop 1:5,000-scale sketch maps of the sites that are approximately tied to UTM coordinates.

Nineteen topographic profiles were measured across scarps in young surficial deposits at the eleven sites using a survey rod and Abney level, following the approach of Bucknam and Anderson (1979). Profile orientations that were perpendicular to the scarp were preferred, but a number of factors complicated the selection of appropriate profile locations. In many cases, all complicating factors could not be avoided. The valleys were usually very narrow where they crossed the faults, and the scarps in the valley-fill deposits were very short in length. This limited the opportunities where profiles could be measured. Colluvium overlies faulted alluvium on the

upthrown sides of some scarps and obscures the original depositional surface of the faulted alluvium, a factor that must be considered when interpreting the profiles.

On the upthrown or upstream sides of the fault, the alluvial sediments usually were confined to narrow valleys. Conversely, on the downthrown/downstream sides of the fault the alluvium was deposited in relatively broad fans that may slope obliquely away from the stream channel. Slope angles and slope directions of the depositional surfaces on the alluvial deposits were commonly different on opposite sides of the scarp. At most sites, the surfaces above the scarps were steeper than the surfaces below the scarps.

Following the approach of Bucknam and Anderson (1979, fig. 3) and McCalpin (1996), the scarp height is the vertical separation between intersections of the plane formed by the steepest part of the scarp face and the planes formed by the displaced original geomorphic surface. They define surface offset as the vertical separation between the projections of the original upthrown and downthrown geomorphic surfaces. If the surfaces are parallel, then their methods are straightforward. But if an upper and steeper surface is projected to where the lower and flatter surface is preserved, then the estimated surface offset may be significantly less than the actual surface offset. Conversely, if the lower, flatter surface is projected to where the steeper upper surface is preserved, the estimated surface offset may be much greater than the actual surface offset. For this study the surface offset was determined by projecting both the upper and lower surfaces to the approximate mid-point of the scarp. The surface offset was assumed to be the vertical separation between these two surfaces. This method has obvious drawbacks, because it is unlikely that the change in surface slopes originally occurred precisely at the midpoint of the scarp. However, this methodology avoids the severe errors that can result from projecting one surface across the entire scarp.

Locally, stream erosion has modified the deposits on the downthrown side of some scarps, which can obfuscate efforts to geometrically analyze scarps. Live standing trees and fallen dead trees were numerous on all profiled scarps, and large boulders, small slumps, and minor gullies were common on some of the scarps; these features created local topographic highs and lows along the profile. Where possible, profile locations were selected to avoid these complicating effects, the obstacles were removed prior to running the profile, or the profile was offset laterally to bypass the obstacle.

The measured profile data were entered into an Excel macro called “Scarp_profiler v2.exl”, which was provided to us by Kathy Haller (USGS). The macro generated the scarp profiles presented herein, and it also calculated various geometric properties of the scarp. To accommodate some of the forementioned complicating factors, the scarp heights and surface offsets were also manually measured using hard copies of the profiles. The manually measured values are reported herein.

Because natural and human-made exposures of the faulted deposits were rare in the study sites, six soil pits were excavated into faulted deposits on the upthrown sides of the faults to help estimate the ages of the faulted deposits. No datable organic materials were recovered from the soil pits. Jim McCalpin (Geo-Haz Consulting, Inc.) described the soil profiles exposed in four of the pits, and the grant contained sufficient funds to analyze grain-size distributions on samples

from those four pits (Appendix A). Sediment smaller than 2 μm in diameter is included in the total clay fraction; fine clay is less than 0.2 μm in diameter.

Ellis (1976) and Rich Madole (2002, personal commun.) studied soils formed on glacial till and outwash in the upper Williams Fork Valley, either at or well upstream of the southern limit of our investigation. Shroba and Birkeland (1983) and Nelson and Shroba (1998) conducted more extensive studies of soils formed on glacial deposits in other nearby areas of central Colorado that have generally similar climate and rock types. We estimated the ages of soils exposed in our soil pits by comparing our soil data to that described in the above references.

The creeks and gulches that deposited alluvium along the northern section of the Williams Fork Mountain fault were not glaciated. Therefore, correlation of the non-glacial alluvium with glacial deposits in other areas is tenuous. Although the headwaters of these streams were not glaciated, they probably accumulated greater amounts of snow during glacial times, which would have resulted in larger discharges during spring runoff. Some of the deposits exposed in the soil pits have sandy gravel and gravelly sand textures suggestive of deposition by fluvial processes. Other deposits, along with the presence of very large 2- to 3-m-diameter boulders in scarps and on the surfaces of the deposits indicate deposition as debris flows. Debris flows are not necessarily associated with glaciation; many occur following wildfires in the headwaters. Debris-flow deposition could occur during periods of glaciation or during interglacial periods, which, in the absence of absolute age dates, complicates efforts to estimate the ages of non-glacial deposits.

REGIONAL GEOLOGIC SETTING

Figure 3 is a generalized geologic map of north-central Colorado. The Williams Fork Valley graben coincides with the area labeled Williams Fork Valley, and it contains extensive deposits of the Miocene Troublesome Formation. Figure 4 is a generalized geologic map of the part of the graben where Quaternary tectonism has been documented. The graben formed during the late Cenozoic in response to extensional stresses that probably were associated with the northern Rio Grande rift (Tweto, 1978, 1979a). The high-angle normal Williams Fork Mountain fault (Figs. 4 and 5) forms the western side of the graben, and unnamed high-angle normal faults bound the eastern side of the graben. A series of northeast-striking, down-to-northwest faults cut obliquely across the floor of the graben.

The leading edge of the east-dipping Laramide (late Cretaceous to Eocene) Williams Range thrust crops out on the west side of the Williams Fork Mountains, where Proterozoic crystalline rocks were thrust over Mesozoic sediments, chiefly thick marine shales of the Pierre Shale (Tweto, 1973, 1976; Tweto and Reed, 1973; Tweto and others, 1978). Subsurface configuration of the thrust fault in this area is poorly constrained, but the mapped pattern of the thrust fault suggests it has a relatively low dip. Kellogg (2001) concluded that the thrust fault had a low dip beneath the southern part of the Williams Fork Mountains, and attributed pervasive fracturing in the landslide-prone crystalline rocks contained in the overthrust block to deformation associated with a shallow underlying thrust fault. Outcrops of Proterozoic

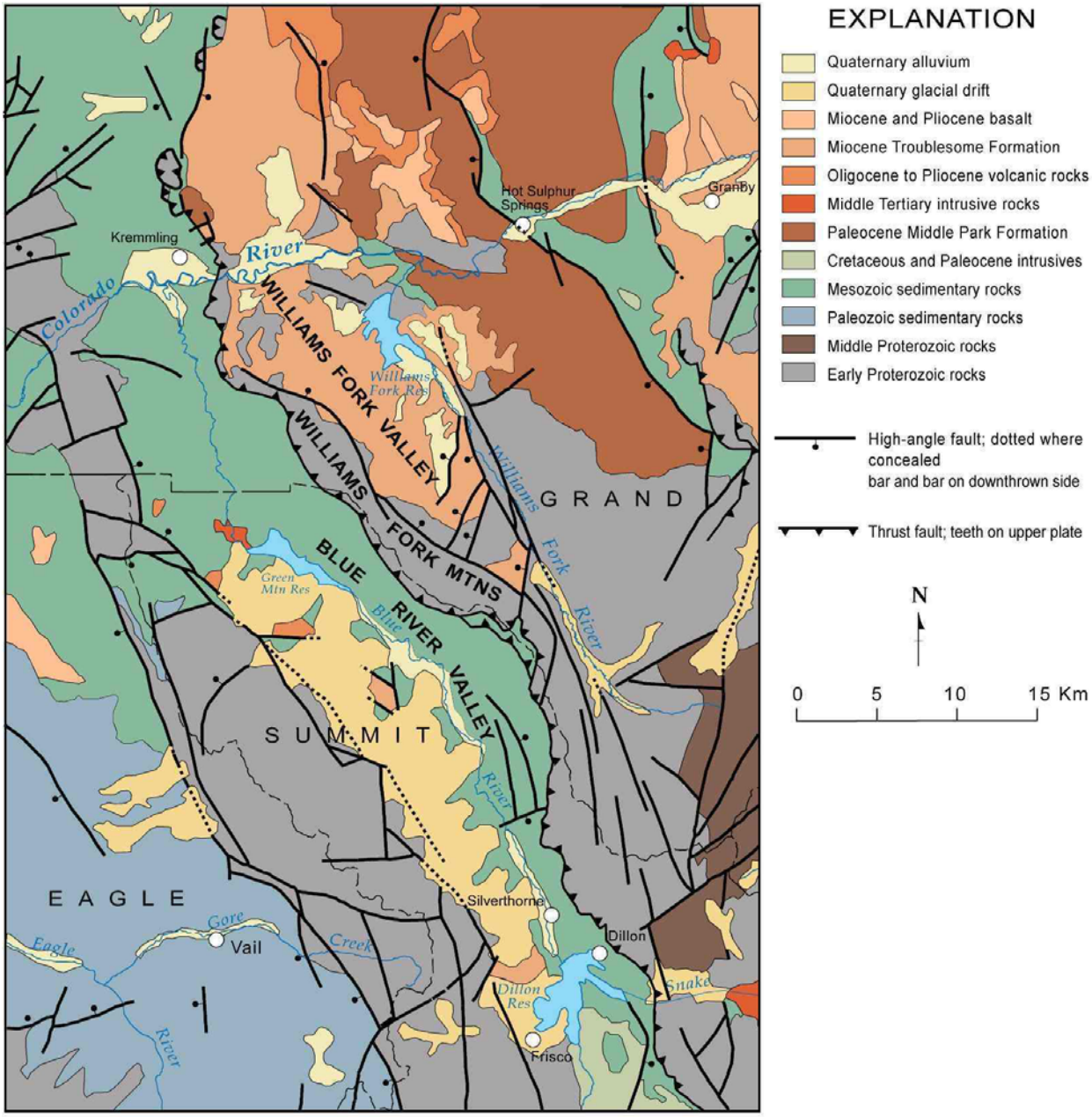

Figure 3. Generalized regional geologic map of north-central Colorado (modified from Tweto, 1979b).

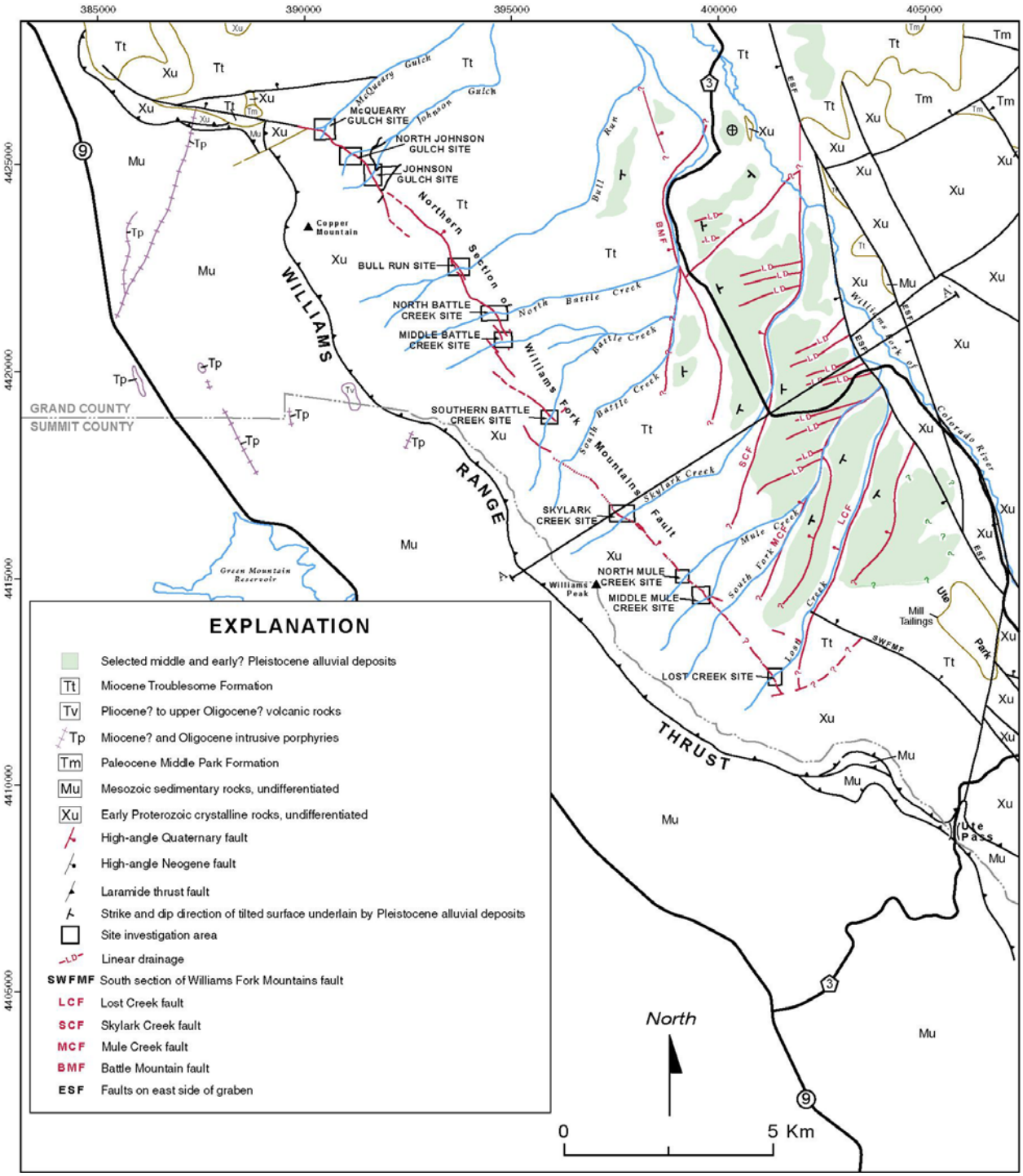

Figure 4. Generalized geologic map of the Williams Fork Valley graben and adjacent areas. Quaternary faults were mapped during this project; other geologic information is from Tweto (1973) and Tweto and Reed (1973).

crystalline rocks are scarce in the northern Williams Fork Mountains, and landslides in the crystalline rocks are common. These factors suggest the rocks are strongly fractured in the northern Williams Fork Mountains, and that the thrust fault may lie at shallow depths beneath it.

In Figure 5, a southwest-northeast cross section across the Williams Fork Valley graben, the Laramide thrust fault is depicted as having an east dip of approximately 25°, and the late Cenozoic Williams Fork Mountains fault is a listric fault that merges with the thrust fault. An alternative model involves steepening of the thrust fault where it merges with the Williams Fork Mountains fault, with both structures being high-angle at depth. The structural configuration of the fault at depth will affect estimates of the maximum credible earthquake for the Williams Fork Mountains fault.

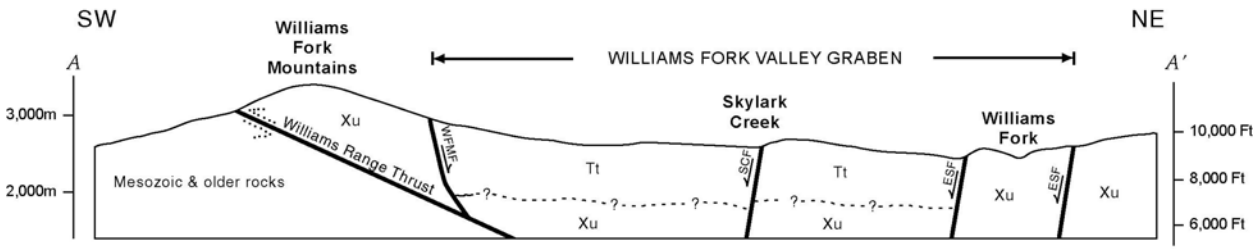

Figure 5. Cross section A-A', a southwest to northeast cross section across the Williams Fork Valley graben. ESF = faults that form the eastern margin of the graben. WFMF = Williams Fork Mountains fault. See Figure 3 for explanations of other symbols and location of the cross section.

NEOTECTONICS OF THE WILLIAMS FORK VALLEY GRABEN

Late Cenozoic tectonism in the Williams Fork Valley graben was first reported by Tweto and Reed (1973) and Tweto (1973), and later summarized by Tweto (1978, 1979a). Kirkham and Rogers (1981) classified the faults that bound the graben and those that lie within the graben as "potentially active". Unruh and others (1993, 1996) reported Holocene movement on the Williams Fork Mountains fault on the basis of work at a single site in Johnson Gulch. Widmann and others (1996, 2002) summarized evidence of late Cenozoic and Quaternary activity on the faults related to the graben. Kirkham and Lindsay (2003) summarized the preliminary findings of this investigation.

Evidence of neotectonism in the Williams Fork Valley graben includes (1) deposition of Neogene graben-filling sediments of the Troublesome Formation, (2) faulting and tilting of the Troublesome Formation, (3) fault-line scarps along the eastern range front of the Williams Fork Mountains, (4) fault scarps in Quaternary surficial deposits along the Williams Fork Mountains fault as far south as Lost Creek, and (5) offset and tilting of middle Pleistocene alluvium by cross faults within the interior of the graben. This investigation focused on evidence of late Quaternary deformation along the Williams Fork Mountains fault at and north of Lost Creek.

Williams Fork Mountains Fault

Geomorphic features indicative of recent tectonism were observed along the northern section of the Williams Fork Mountains fault on aerial photography, LANDSAT imagery, and shaded relief DEMs during the initial phase of the study. These features include faceted spurs on the mountain front, topographic, vegetational, and tonal lineaments, truncated ridgelines, uphill-facing escarpments, and abundant landslides, some of which were reported previously by Unruh and others (1993, 1996). These features are present as far south as Lost Creek, but photogeologic evidence of young fault activity was not detected south of Lost Creek. These observations are supported by the work of Wong and others (1995), who subdivided the fault into a northern section with probability of activity of 100% and a southern section with probability of activity of only 10%, and by the work of Unruh and others (1993, 1996). Subsequent field work conducted during this investigation found many fault scarps in young alluvium along the northern section of the Williams Fork Mountains fault from McQueary Gulch on the north, to Lost Creek on the south, a distance of about 18 km.

Our reconnaissance field studies along the southern section of the fault did not yield conclusive evidence of recent faulting. The southern section of the fault lies within Proterozoic rock for much of its approximately 18 km length, and there are few locations where crosscutting relationships between the fault and middle to late Pleistocene sediments can be observed. It is possible that the southern section has been inactive during the late Quaternary, has a reduced slip rate relative to other sections of the fault, or that the evidence of recent activity is poorly preserved. In the northwest corner of Ute Park, the southern section of the fault, as mapped by Tweto and Reed (1973), forms a linear fault-line scarp. Unfortunately, this area has been disturbed by work associated with the Henderson mill tailings pond, which could obscure any evidence of late Quaternary faulting that existed here.

Aerial photography was of limited use in determining whether topographic scarps were present in the young valley-fill deposits along the fault trace. Therefore, a decision was made to conduct foot traverses along the northern section of the Williams Mountains fault to search for scarps in young deposits. This proved to be very time consuming, due to the rough terrain and limited public access. Prominent scarps were present in the surficial deposits in all the valleys, but some scarps were suspected to have non-tectonic origins such as fluvial erosion, boulder deposits associated with distal ends of debris flows, and landsliding.

To distinguish tectonic scarps from non-tectonic scarps, we first located the fault on the interfluves where Proterozoic crystalline rocks were faulted against sediments of the Troublesome Formation. Well-preserved fault-line scarps marked the fault on many of the interfluves. Where present, the fault-line scarps were traced to the adjacent valleys. Scarps in young surficial deposits that coincided with the fault-line scarp were assumed to be a result of tectonism, unless other evidence indicated a non-tectonic origin for the scarp. If fault-line scarps could not be traced to a valley floor, then additional work was not conducted on the scarps in that valley.

One section of the mountain front, approximately from North Battle Creek to Skylark Creek, lacks well-developed faceted spurs and fault-line scarps. In this area, large landslides initiated in Proterozoic rocks in the footwall of the fault and slid across the fault, coming to rest on the hanging wall and effectively concealing or altering the tectonic geomorphology of the range front. After discovering this impedance, further work along this section of the fault was postponed. The landslides on the east side of the Williams Fork Mountains are probably similar in origin to large landslides described by Kellogg (2001) on the west side of the range. He attributed the landslides on the west side of the range to slope failures in strongly fractured Proterozoic rocks found in the overhanging block of the Laramide-age Williams Range thrust.

The fault scarps along the northern section of the Williams Fork Mountains fault are not gravitational-spreading features like those described by Varnes and others (1989) in the southern Williams Fork Mountains. These sackungen occur at and near the range crest, and many are uphill facing. The scarps along the Williams Fork Mountains fault lie at the base of the range and are downthrown toward the valley.

Geologic sketch maps were prepared for eleven sites along the northern section of the Williams Fork Mountains fault (Fig. 4). Topographic profiles were measured across at least one scarp at each site. The valleys were commonly very narrow where they crossed the fault, therefore the scarps in surficial deposits were generally very short, and many were modified by subsequent fluvial erosion, colluvial deposition, and slumping. The following sections summarize the evidence of late Quaternary faulting at the eleven sites, starting in the south and working northward.

Lost Creek Site

Lost Creek site is on an unnamed tributary in the headwaters of Lost Creek (Fig. 4). The site is near the southern end of the northern section of the Williams Fork Mountains fault. About 0.5 km south of the Lost Creek site, the northern section of the fault appears to abut against an east-northeast-trending lineament that may be associated with a Quaternary fault (Fig. 4). The lineament was not field checked during this study.

A single scarp cuts alluvial deposits of two ages at the Lost Creek site (Fig. 6), including the youngest valley-fill deposits (unit Qa1). Profile LC-P1 (Fig. 7) was measured across the scarp in unit Qa1. The scarp is 1.6 m high, the surface offset is estimated at 1.1 m, and the maximum scarp angle (θs) is 16.5^{o}. The subtle topographic low at the base of the scarp may reflect the presence of an antithetic fault and shallow graben. A second profile (LC-P2; Fig. 8) characterizes the scarp in unit Qa2. Profile LC-P2 is perpendicular to the scarp, but the profile is oblique to the faulted alluvial fan surface. There is a prominent topographic depression at the base of this scarp. Initially the landform was interpreted as a landslide headscarp, but on closer examination we concluded it was a small graben with odd orientation due to the oblique relationship of the profile to the fan surface. This topographic depression complicates interpretation of the scarp profile. We estimate the scarp height is 2.2 m, and the surface offset is 2.0 m. The maximum scarp angle is 25.5^{o}.

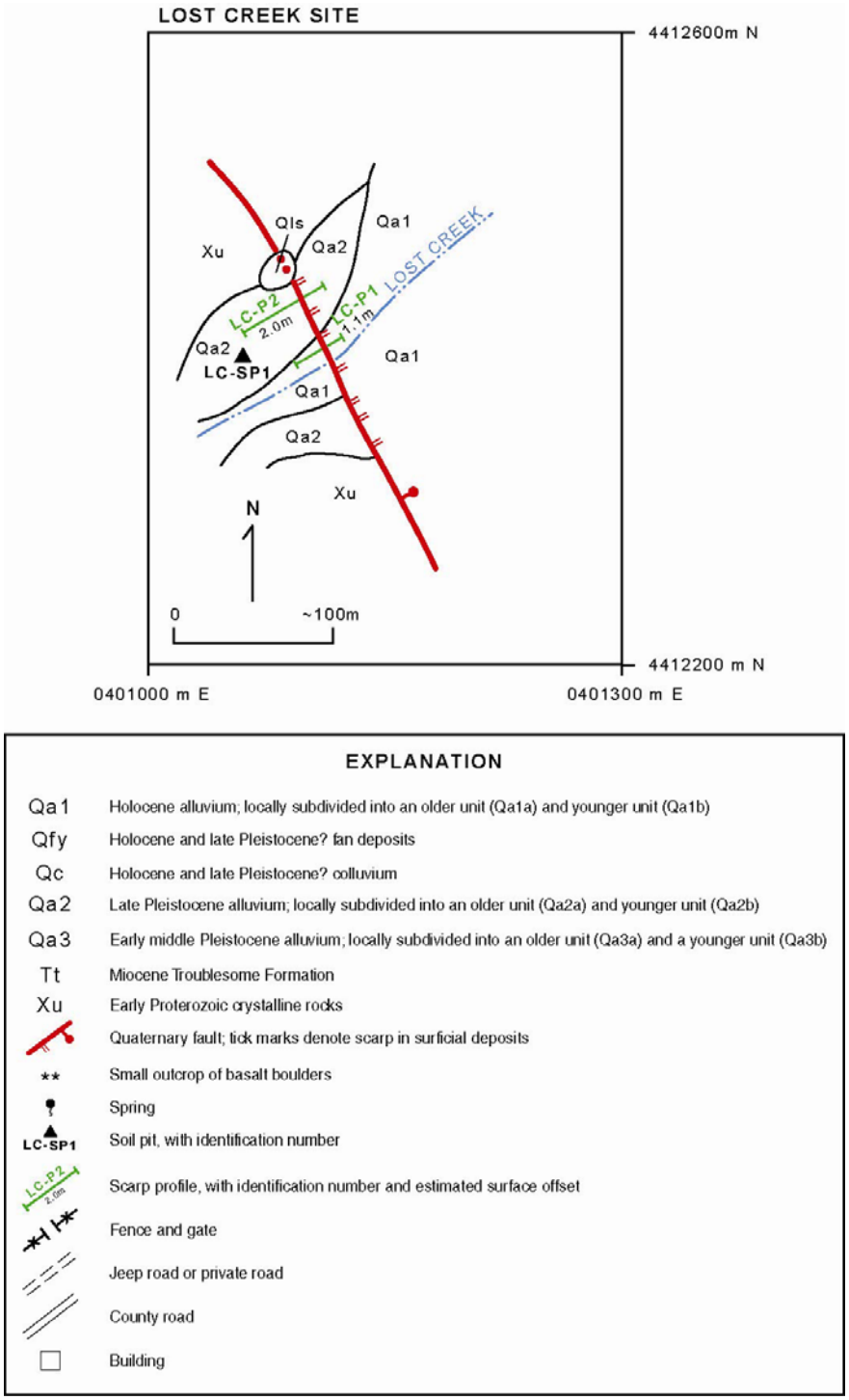

Figure 6. Geologic sketch map of Lost Creek site. See Figure 4 for location of site. Explanation applies to all site sketch maps.

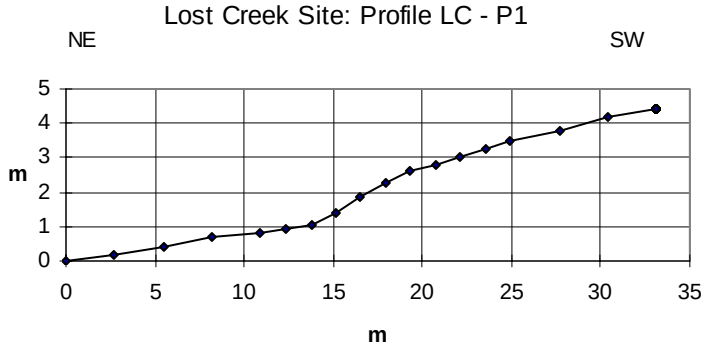

Figure 7. Profile LC-P1, Lost Creek site. Vertical exaggeration is ~2x; scarp height = 1.6 m; surface offset = 1.1 m; maximum scarp angle (θs) = 16.5^{o}. See Figure 6 for location of profile.

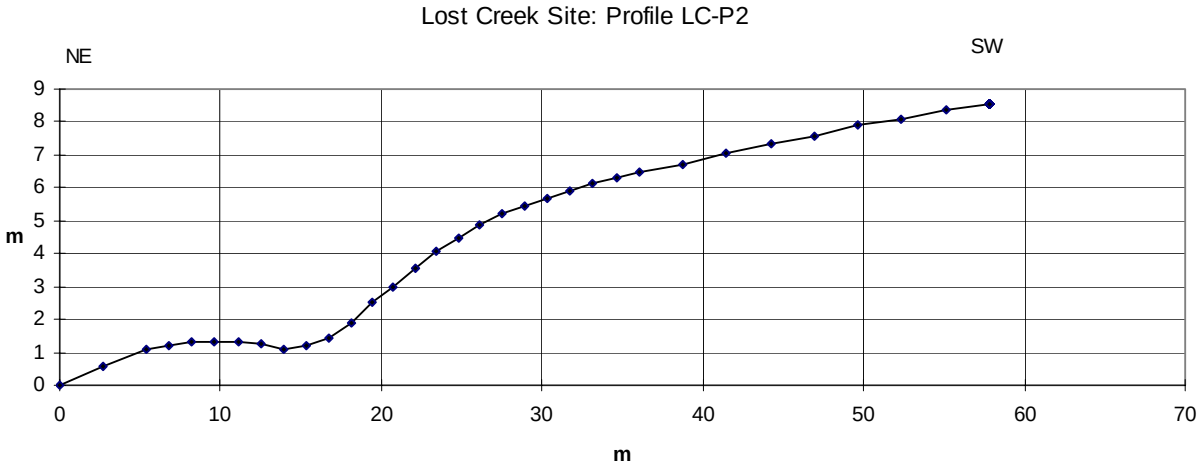

Figure 8. Profile LC-P2, Lost Creek site. Vertical exaggeration is ~2x; scarp height = 2.2 m; surface offset = 2.0 m; maximum scarp angle = 25.5^{o}. See Figure 6 for location of profile.

Soil pit LC-SP1 was excavated into unit Qa2 on the upthrown side of the fault. Figure 9 depicts the soil profile, total and fine clay content of each soil horizon, and parent material for this pit. Of the four pits examined during the study, pit LC-SP1 contained the strongest developed soil. The Bt horizon was 35 cm thick, contained 10% total clay, and had weak to moderate, medium to fine, subangular blocky texture. The combined thickness of the EB, Bt, and BC horizons is 55 cm. The total clay content of the Bt horizons is equal to or at most 2% more than that in the C1ox and C2ox horizons, and the fine clay increased even lesser amounts, suggesting only minor accumulation of clay in the Bt horizon. A possible buried Bw horizon underlies the Cox horizon of the upper soil sequence. Granitic and gneissic clasts in the upper soil are moderately decomposed.

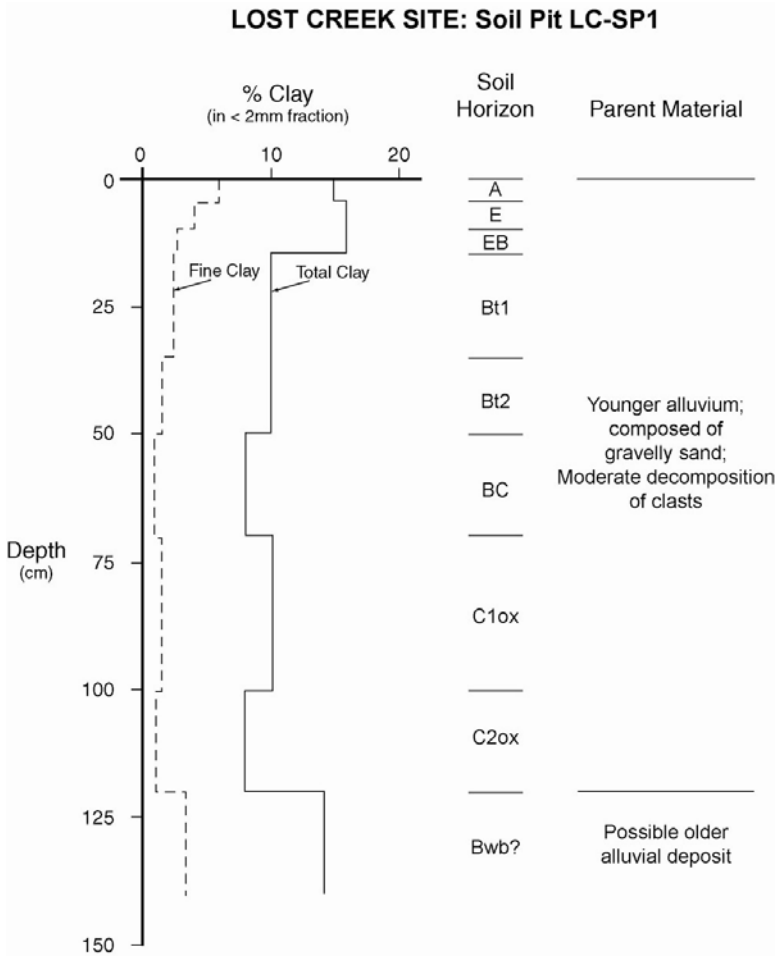

Figure 9. Pedogenic soil profiles, clay content of soil horizons, and parent material in soil pit LC-SP1 at Lost Creek site. See Figure 6 for location of soil pit.

We conclude unit Qa2 is late Pleistocene in age, and perhaps is correlative with the Pinedale glaciation (12-35 ka, Richmond, 1986), on the basis of comparisons to the soils described by Nelson and Shroba (1998), Shroba and Birkeland (1983), and Ellis (1976). The soil is more developed than those on Holocene deposits, which usually lack any B horizon, and less developed than those on Bull Lake deposits, which have thicker Bt horizons and greater clay accumulation. Unit Qa1 is lower in elevation and closer to the creek than unit Qa2, and is interpreted as a Holocene deposit.

Middle Mule Creek Site

Middle Mule Creek site is on the southerly of the two branches of the main fork of Mule Creek (Fig. 4). A single fault scarp occurs along the range front at this site (Fig. 10). A second scarp inferred to be of tectonic origin starts at the eastern margin of the site and extends southeastward. The valley of "middle" Mule Creek is relatively wide, and the scarp in this valley is over 200 m long. It is the longest scarp found along the Williams Fork Mountains faults during

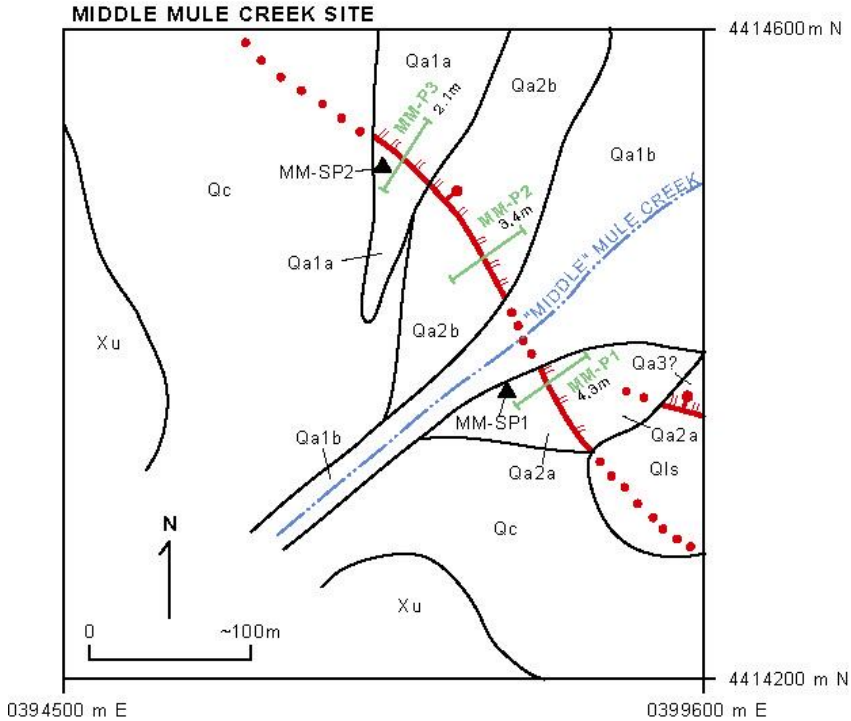

Figure 10. Geologic sketch map of Middle Mule Creek site. Refer to Figure 4 for location of site and Figure 6 for explanation of symbols.

the investigation. The scarp cuts deposits of three ages: units Qa1a, Qa2b, and Qa2a. The youngest deposit at the site, unit Qa1b, conceals the fault. Units Qa1b, Qa2a, and Qa2b were deposited as stream alluvium by this perennial-flowing fork of Mule Creek, whose head extends to the crest of the mountain range. Unit Qa1a consists of reworked colluvium that was locally deposited by an ephemeral tributary with very small drainage basin. The creek has incised only 1 to 1.5 m into unit Qa1b on the downthrown side of the fault, but on the upthrown side of the fault it has cut approximately 8.4 m into unit Qa2a and about 7 m into unit Qa2b.

Three profiles were measured at the Middle Mule Creek site, one in each of the faulted deposits. Profile MM-SP1 (Fig. 11) crosses the scarp in unit Qa2a, which underlies the topographically highest and oldest fan remnant at the site. The scarp height in unit Qa2a is 6.6 m, the surface offset is 4.3 m, and the maximum scarp angle is 28.0^{o}. Unit Qa2a may be concealed by a thin deposit of a younger unit on the downthrown side of the scarp. Therefore, the surface offset of unit Qa2a may exceed the measured offset. Profile MM-SP2 (Fig. 12) characterizes the scarp in unit Qa2b. Scarp height in unit Qa2b is 4.4 m, surface offset is 3.4 m, and maximum scarp angle is 22.5^{o}. A thin veneer of younger alluvium may overlie unit Qa2b in the vicinity of the bottom of this scarp profile. The scarp profile in unit Qa1a (profile MM-SP3) is shown in Figure 13. The scarp is 2.7 m high in unit Qa1a, the surface offset is 2.1 m, and the maximum scarp angle is 21.5^{o}. A nearly 1-m-deep topographic depression visible on the upthrown side of the scarp in profile MM-P3 is a small gully that runs obliquely across the line of the profile.

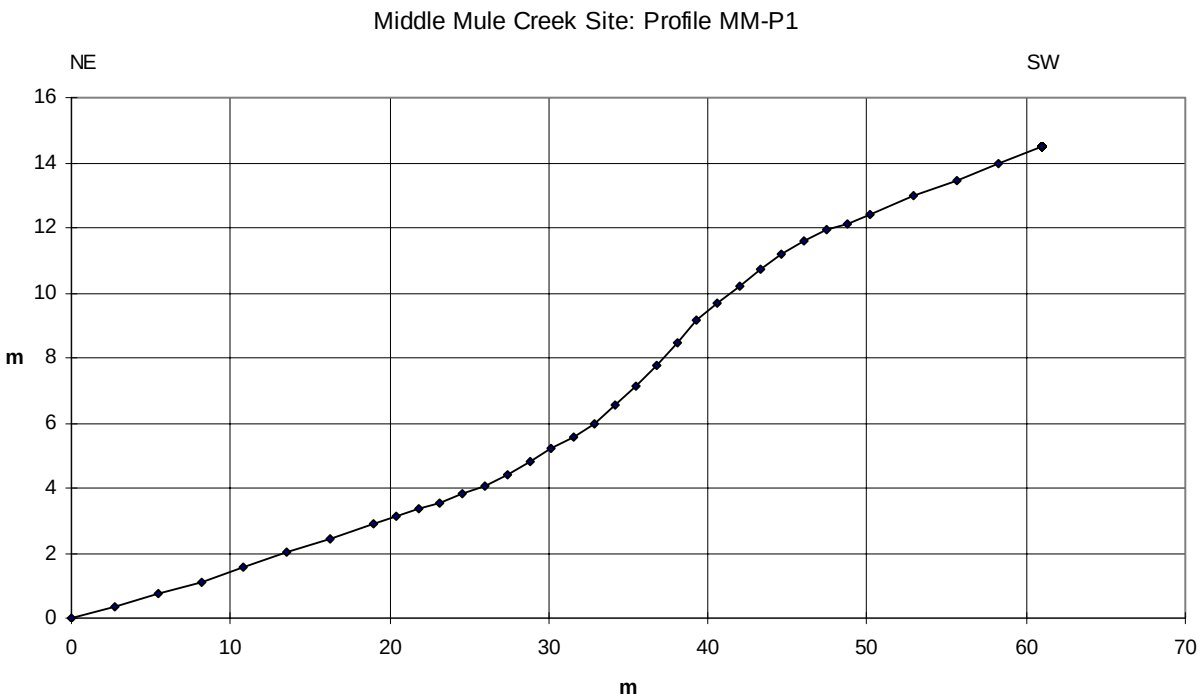

Figure 11. Profile MM-P1, Middle Mule Creek site. Vertical exaggeration is ~2x; scarp height = 6.6 m; surface offset = 4.3 m; θs = 28.0°. See Figure 10 for location of profile.

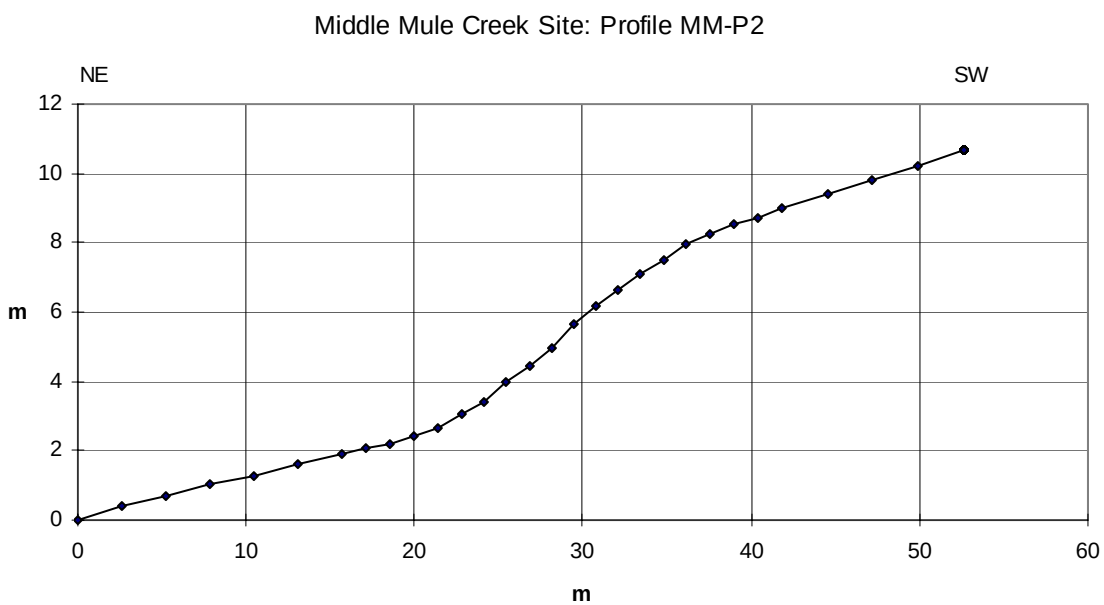

Figure 12. Profile MM-P2, Middle Mule Creek site. Vertical exaggeration is ~2x; scarp height = 4.4 m; surface offset = 3.4 m; θs = 22.5°. See Figure 10 for location of profile.

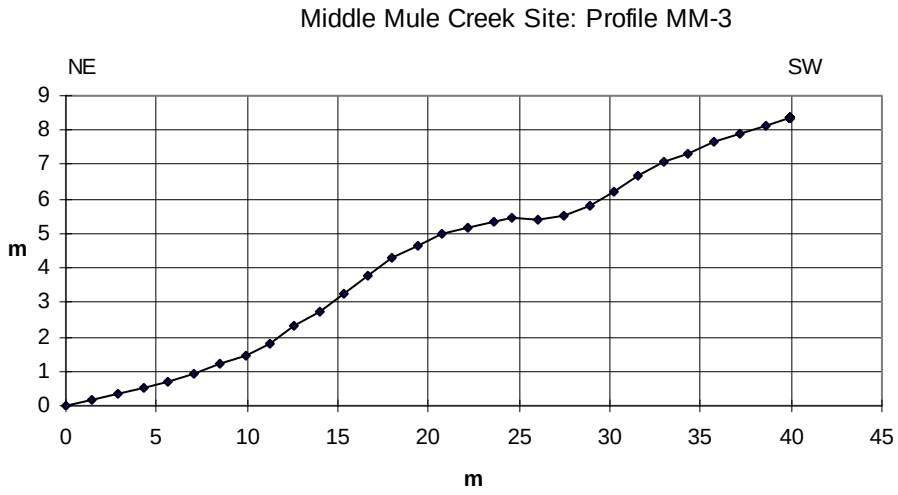

Figure 13. Profile MM-P3, Middle Mule Creek site. Vertical exaggeration is ~2x; scarp height = 2.7 m; surface offset = 2.1 m; θs = 21.5^{o}. See Figure 10 for location of profile.

Two soil pits were excavated at the Middle Mule Creek site. Pit MM-SP1 (Fig. 14) was dug into unit Qa2a, the oldest faulted deposit; pit MM-SP2 (Fig. 15) was excavated into unit Qa1b, the youngest faulted unit. The parent material exposed in the upper 60 cm of pit MM-SP1 was a boulder-rich alluvium with a weakly developed soil. A Bw horizon with very weak, medium subangular blocky structure was present from 17 to 30 cm. Total clay content increased about 3% in the Bw horizon relative to the underlying Cox horizon, but fine clay only increased about 1%. None of the granitic and gneissic clasts were decomposed, suggesting the upper deposit is probably early Holocene. The lower 70 cm exposed in pit MM-SP1 consisted of Cox and Cn horizons; any A and B horizons that may have originally been present were stripped by erosion prior to deposition of the overlying 60-cm-thick unit. Clasts within the lower unit were moderately decomposed, similar to those present in pit LC-SP1 at the Lost Creek site. We conclude the sediments exposed in the upper part of pit MM-SP1 are late Pleistocene in age and probably correlate with the Pinedale glaciation (12-35 ka; Richmond, 1986). The lower unit exposed in soil pit MM-SP-1 may be Bull Lake in age. The Bull Lake is considered to be 140 to 150 ka by Pierce and others (1976) and Pierce (1979), and 130 to 350 ka by Richmond (1986).

Soil pit MM-SP2 exposed two soil horizons in unit Qa1a. A soil profile consisting of an A horizon, 10-cm-thick Bx horizon, and 6-cm-thick Cox horizon was present in the upper 23 cm of the pit. The Bw horizon was weak, lacked soil structure, and its total clay content was only

1% greater than that of the A horizon and 3% greater than the Cox. The fine clay content of the Bw horizon was less than 1% greater than that of the A and Cox horizons. The buried soil included a 20-cm-thick Eb horizon and 57-cm-thick Cox horizon, but lacked a B horizon. No clast decomposition was present in either soil sequence. These deposits of unit Qa1a are probably Holocene in age, perhaps early Holocene (~10 ka), or they may be correlative with deposits of the latest Pinedale glaciation (~12 ka). The unfaulted unit Qa1b likely is Holocene, possibly late Holocene (<5 ka). Unit Qa2b is older than unit Qa1a and younger than unit Qa2a, and is assumed to be age equivalent to the Pinedale glaciation.

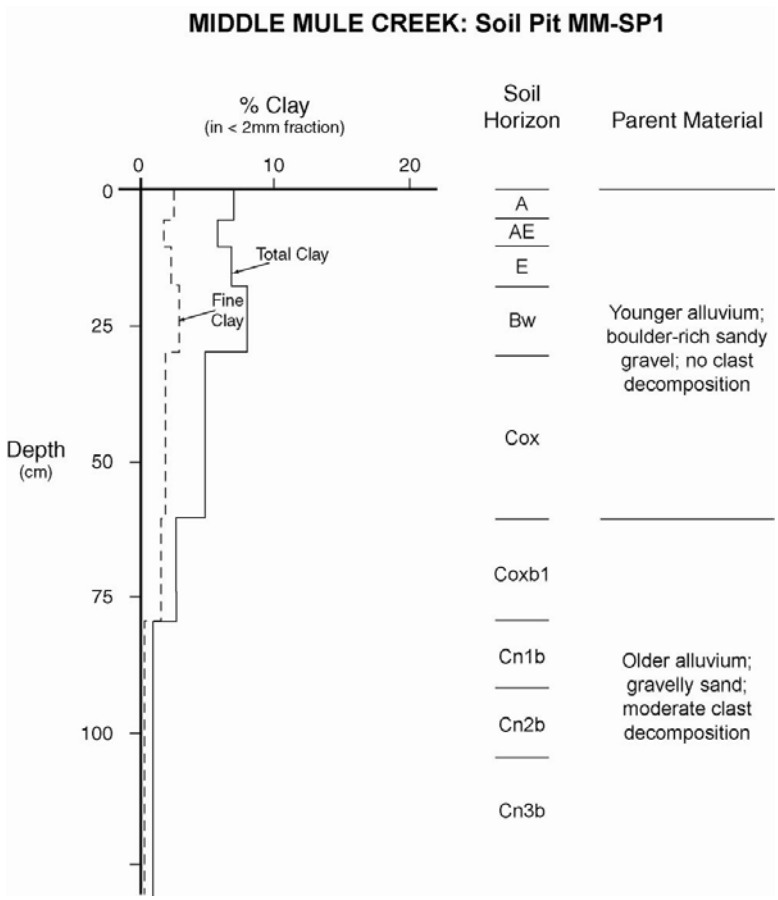

Figure 14. Pedogenic soil profiles, clay content of soil horizons, and parent material in soil pit MM-SP1 at Middle Mule Creek site. See Figure 10 for location of soil pit.

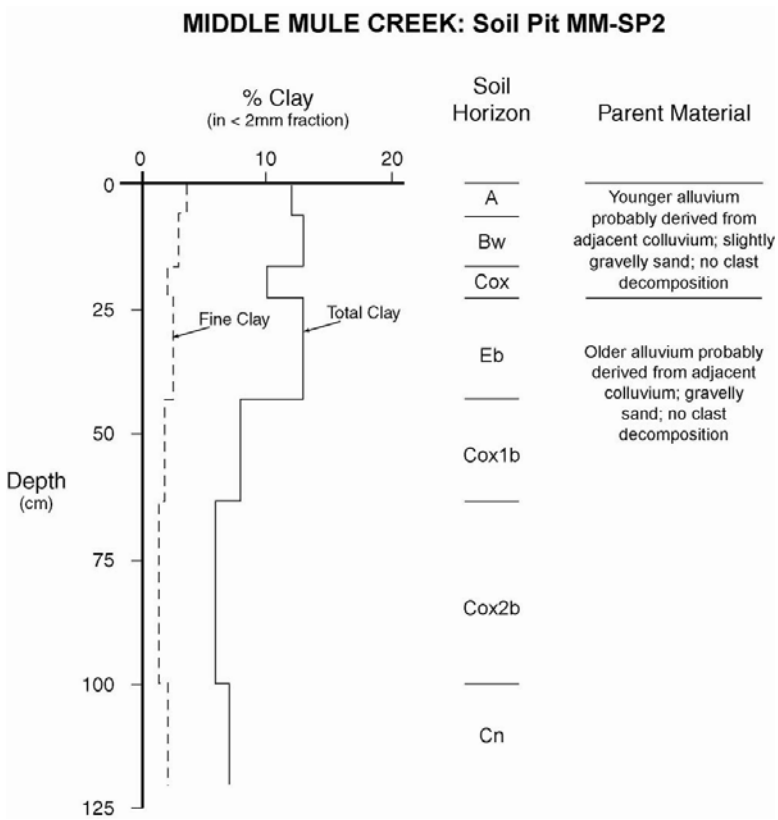

Figure 15. Pedogenic soil profiles, clay content of soil horizons, and parent material in soil pit MM-SP2 at Middle Mule Creek site. See Figure 10 for location of soil pit.

North Mule Creek Site

North Mule Creek site is situated on the northernmost fork of Mule Creek (Fig. 4). On the north side of the creek, a scarp about 100 m long cuts the deposits of a remnant of an alluvial fan (unit Qa3; Fig. 16). The surface of the fan is about 10.4 m higher than the adjacent creek on the downstream side of the scarp and about 16.8 m above the creek on the upstream side. A single profile, NM-P1, was measured at this site (Fig. 17). The scarp height is about 5.8 m, surface offset is about 4.0 m, and maximum scarp angle is 25.0^{o}. Limited data are available to assess the age of unit Qa3. The surface offset is similar to that of units Qa2a and Qa2b at the Middle Mule Creek site, but the fan surface present on faulted deposit Qa3 at the North Mule Creek site is about two times higher above the adjacent stream than is the surface on unit Qa2a at Middle Mule Creek site. This leads us to conclude that the faulted Qa3 deposit at the North Mule Creek site may be older than unit Qa2a at Middle Mule Creek site, and perhaps is correlative with deposits of the Bull Lake glaciation, which may be 140 to 150 ka (Pierce and others, 1976; Pierce, 1979) or 130 to 350 ka (Richmond, 1986).

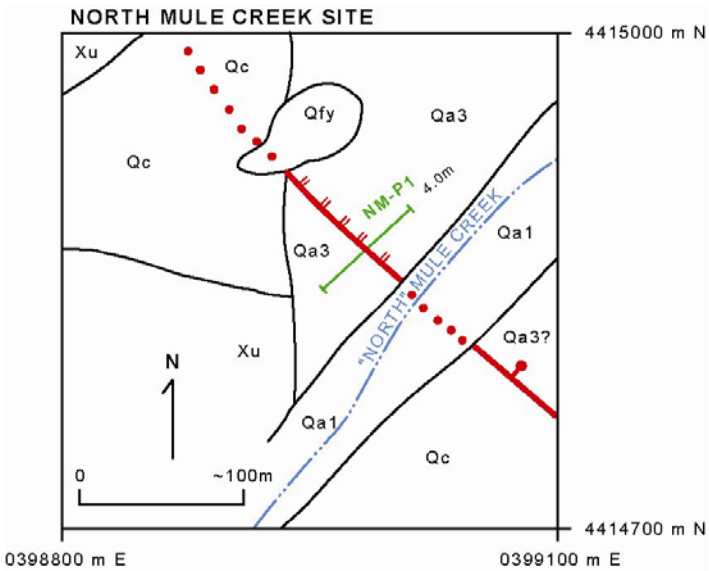

Figure 16. Geologic sketch map of North Mule Creek site. Refer to Figure 4 for location of site and Figure 6 for explanation of symbols.

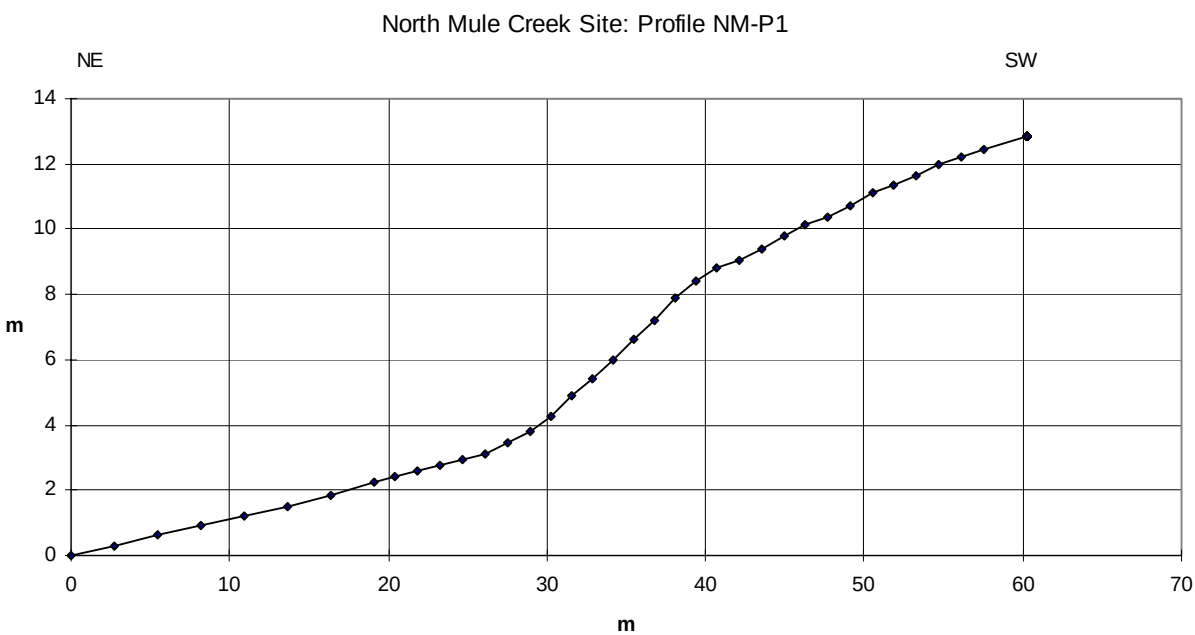

Figure 17. Profile NM-P1, North Mule Creek site. Vertical exaggeration is ~2x; scarp height = 5.8 m; surface offset = 4.0 m; θs = 25.0°. See Figure 16 for location of profile.

Skylark Creek Site

The Skylark Creek site is on the northernmost fork of Skylark Creek (Fig. 4). A single scarp cuts a remnant of an older fan on the north side of the creek (Fig. 18). The surface of this fan is about 23.5 m above the creek floor on the upstream side of the scarp. Profile SC-P1 (Fig. 19) was measured across the scarp in the faulted deposit on the north side of the creek. The scarp is 6.2 m high, with a surface offset of 2.6 m and maximum scarp angle of 20.5^{o}. The faulted deposit at Skylark Creek site is nearly 40% higher above the creek than the faulted deposit at the North Mule Creek site, however, the scarp height and surface offset is less at the Skylark site than at the North Mule Creek site. The faulted surface at Skylark Creek site is nearly three times as high above the creek as the surface on unit Qa2a at the Middle Mule Creek site, yet the surface offset at the Skylark site is only 60% of that in unit Qa2a at the Middle Mule Creek site.

In the absence of additional relative or absolute age control, we infer the faulted unit at the Skylark Creek site (Qa3) is correlative to deposits of the Bull Lake glaciation. Possible explanations for this apparent anomaly involving an older deposit with a smaller scarp include: (1) the rate of uplift on both sides of the fault in the Skylark Creek and Northern Mule Creek sites is higher than the rates at the Middle Mule Creek site, in which case we have overestimated the age of the deposit; (2) slip rates at the Middle Mule Creek site are greater than the rates at the Skylark Creek or Northern Mule Creek sites; (3) base level of Skylark and North Mule creeks well downstream from the scarps has lowered more rapidly than the base level of Middle Mule

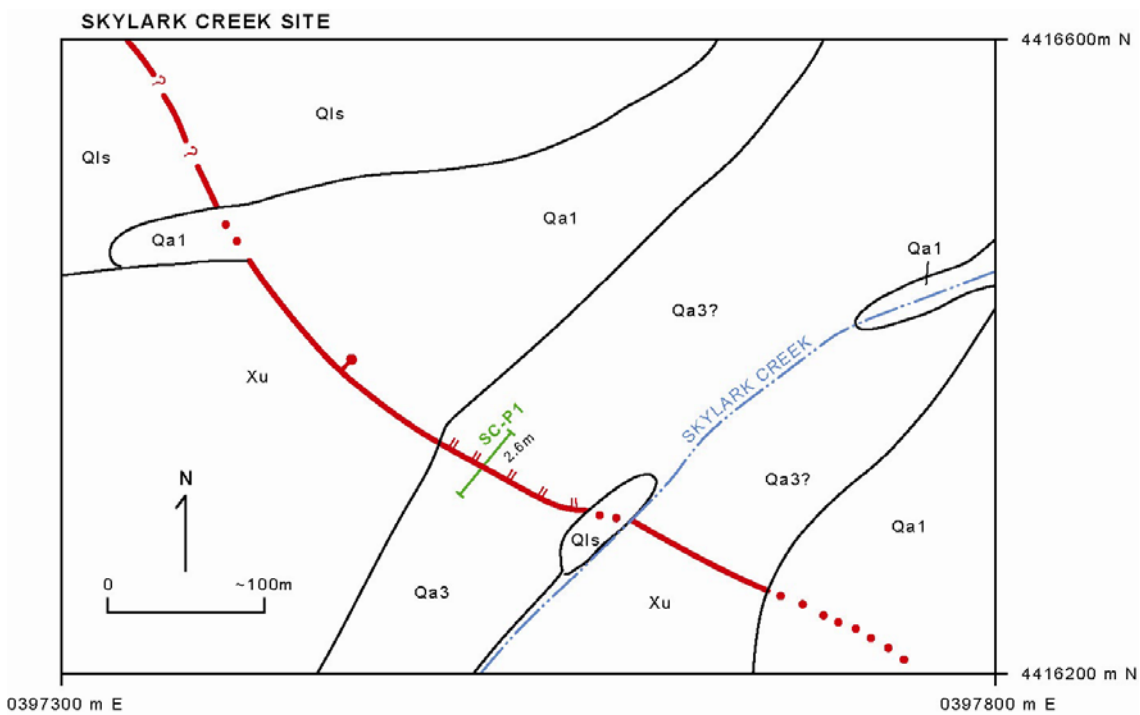

Figure 18. Geologic sketch map of Skylark Creek site. Refer to Figure 4 for location of site and Figure 6 for explanation of symbols.

Creek, perhaps reflecting differing slip rates on the larger cross faults within the interior of the graben, which could cause accelerated incision at the Skylark and North Mule creek sites; and (4) our estimates of the ages of these deposits are incorrect.

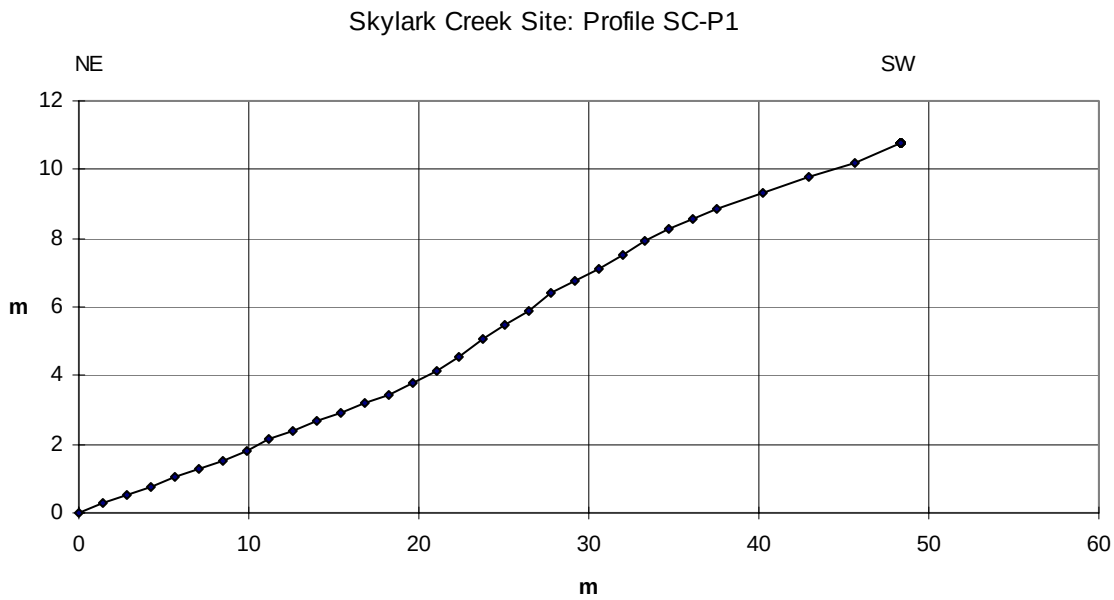

Figure 19. Profile SC-P1, Skylark Creek site. Vertical exaggeration is ~2x; scarp height = 6.2 m; surface offset = 2.6 m; θs = 20.5°. See Figure 18 for location of profile.

Southern Battle Creek site

The Southern Battle Creek site is located on the southernmost branch of the main fork of Battle Creek (Fig. 4). The single, relatively short, poorly expressed, and somewhat eroded fault scarp at this site is interpreted to cut a small remnant of an alluvial fan (unit Qa2) on the north side of the creek (Fig. 20). On the upthrown side of the scarp, the surface of this faulted fan remnant is about 9 m higher than the creek. The deposit on the downthrown side of the scarp probably correlates with the deposit on the upthrown side of the scarp. Two alluvial units conceal the fault: a younger deposit of alluvium associated with the modern stream (unit Qa1b), and a slightly higher and older deposit (unit Qa1a).

Profile SB-P1 (Fig. 21) crosses the scarp in unit Qa2. Scarp height is 4.4 m, surface offset is about 3.0 m, and the maximum scarp angle is 16.0°. A thin veneer of colluvium eroded from crystalline bedrock in the adjacent hillslope is present on the upthrown side of the scarp. This material complicates accurate determination of the geometric properties of the scarp. Units Qa1a and Qa1b are probably Holocene, and unit Qa2 is inferred to be late Pleistocene.

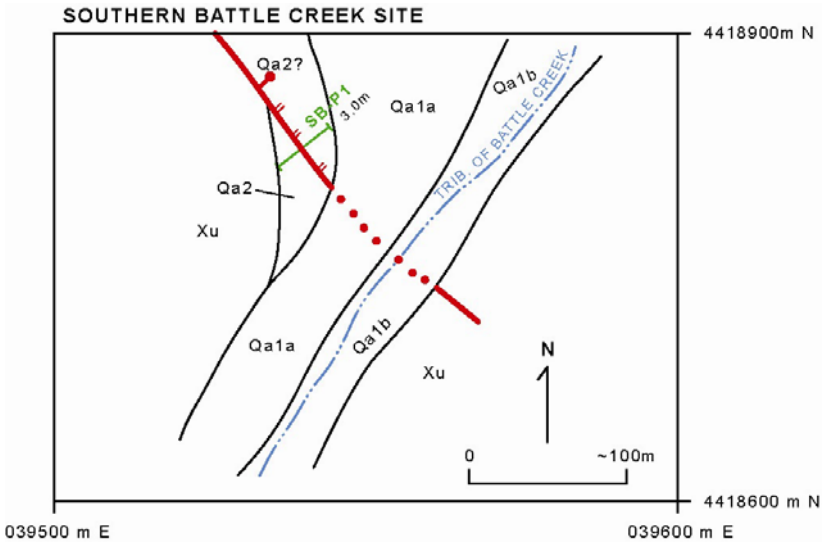

Figure 20. Geologic sketch map of Southern Battle Creek site. Refer to Figure 4 for location of site and Figure 6 for explanation of symbols.

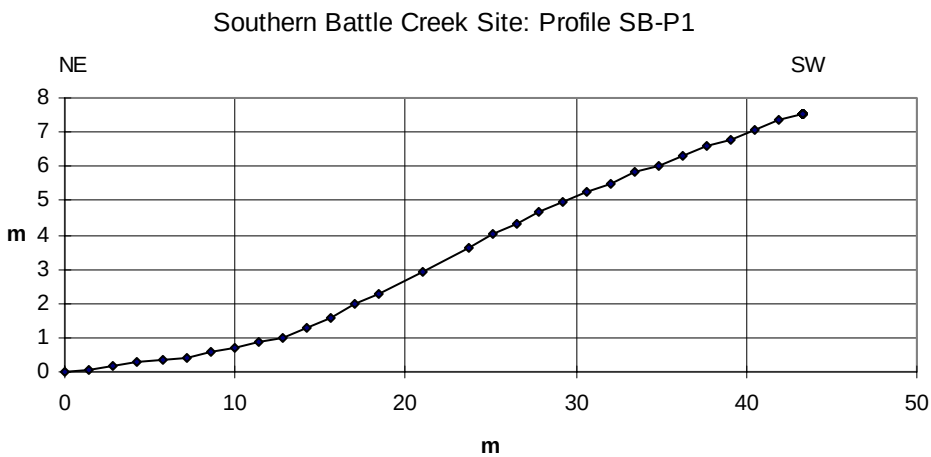

Figure 21. Profile SB-P1, Southern Battle Creek site. Vertical exaggeration is ~2x; scarp height = 4.4 m; surface offset = 3.0 m; θs = 16.0^{o}. See Figure 20 for location of profile.

Middle Battle Creek Site

Middle Battle Creek site is situated on the northern branch of the main fork of Battle Creek (Fig. 4). The Williams Fork Mountains fault consists of several en echelon splays in this area. Two of the splays are shown on the Middle Battle Creek site map (Fig. 22), and a third lies

west of the site. Other subtle topographic scarps in the area potentially have a tectonic origin. The eastern splay connects with the range-front fault north of the site, and the western splay is part of a short fault segment that forms a good fault-line scarp to the north. As at the Southern Battle Creek site, there are two deposits of alluvium (units Qa1a and Qa1b) that conceal the fault splays, and one deposit (unit Qa2) that is cut by the splays. The surface on unit Qa1a is about 3 m higher than the creek, and the surface on unit Qa2 is an estimated 8 to 10 m above the creek.

Profiles were measured across both scarps in unit Qa2. Profile MB-P1 (Fig. 23) characterizes the eastern splay, which has a scarp height of 3.2 m, surface offset of 2.3 m, and maximum scarp angle of 14.5^{o}. A subtle topographic steepening near the southwest end of the profile near horizontal distance 52 m may reflect a minor scarp. Profile MB-P2 (Fig. 24) is on the western splay. The main scarp on this profile is near the northeast end of the profile; it is 3.8 m high, has a surface offset of 2.5 m, and a maximum scarp angle of 18.5^{o}. The step near the northwest end of the profile (near horizontal distance 44 m) also could be a small tectonic scarp. If it is a tectonic scarp, then the combined scarp height for both of the scarps totals about 4.6 m and the combined surface offset is about 3.6 m. Units Qa1a and Qa1b are interpreted as Holocene deposits, and unit Qa2 may be late Pleistocene in age; additional age control is needed to confirm these age estimates.

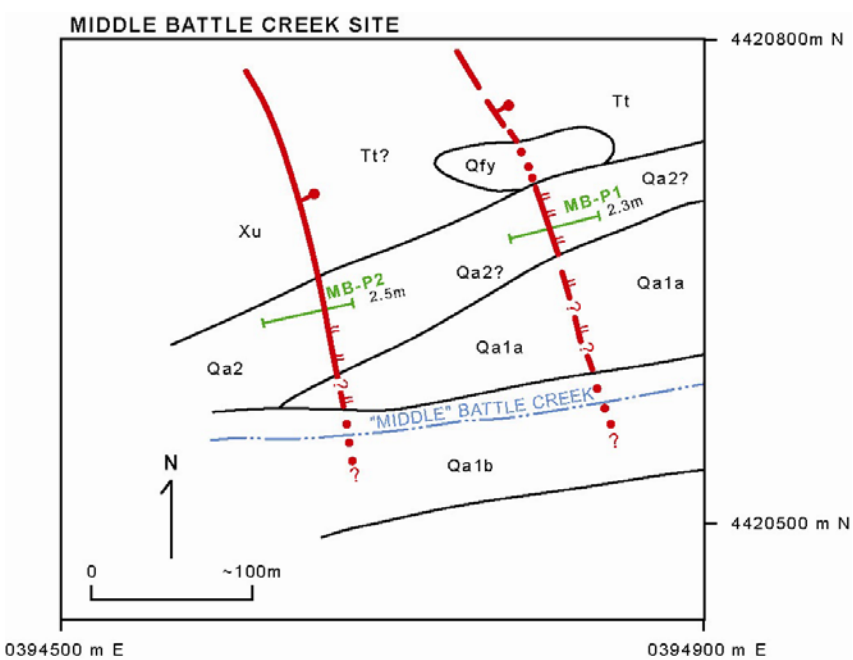

Figure 22. Geologic sketch map of Middle Battle Creek site. Refer to Figure 4 for location of site and Figure 6 for explanation of symbols.

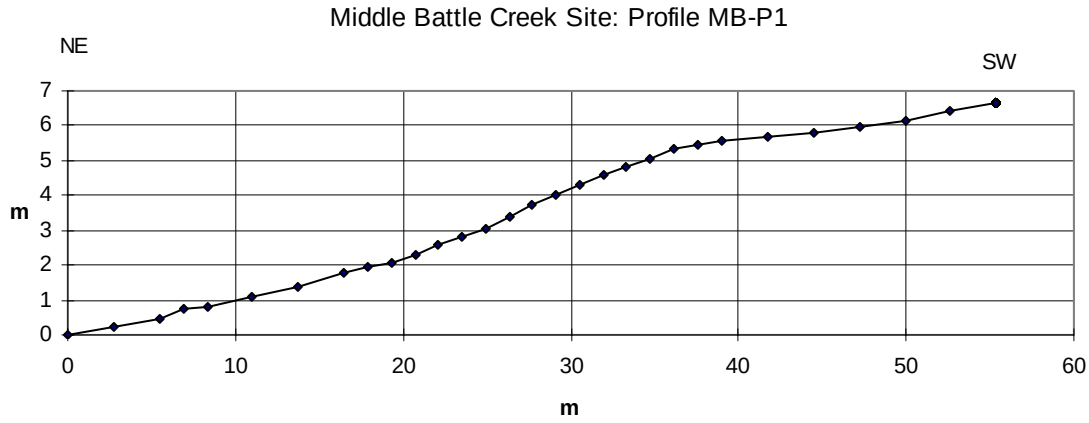

Figure 23. Profile MB-P1, Middle Battle Creek site. Vertical exaggeration is ~2x; scarp height = 4.4 m; surface offset = 2.3 m; θs = 14.5°. See Figure 22 for location of profile.

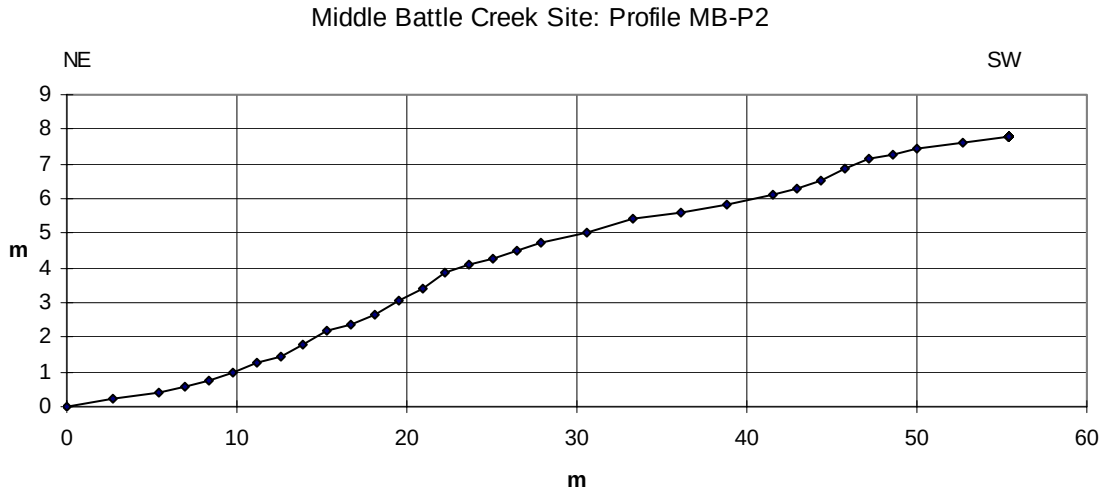

Figure 24. Profile MB-P2, Middle Battle Creek site. Vertical exaggeration is ~2x; scarp height = 3.8 m; surface offset = 2.5 m; θs = 18.5°. See Figure 22 for location of profile.

North Battle Creek Site

The North Battle Creek site lies on the main fork of North Battle Creek (Fig. 4), north of the area with en echelon splay faults that are near the Middle Battle Creek site. A single scarp in surficial deposits of two ages is present on the south side of North Battle Creek (Fig. 25). Modern alluvium along the creek conceals the fault. The scarp ties to a well-developed fault-line

scarp on the north side of the creek. Two profiles were recorded at this site. Profile NB-P1 (Fig. 26) runs across the scarp in unit Qa1a, and profile NB-P2 characterizes the scarp in unit Qa3b. Unfortunately, the creek sweeps southward on the downstream side of the scarp, therefore younger alluvium is present at the surface on the downthrown side of the scarp at both profiles. An older unit (Qa3?) is present on the downstream side of the scarp on the south side of the valley, but it was not possible to measure a profile at this location. The values reported for the surface offsets for both profiles compare the surface on the younger deposit below the scarp to the surface on the older deposits that are present on the upthrown side of the scarp. The actual surface offset of the older deposits may be greater than or less than the reported values.

On profile NB-P1, the scarp height is 1.4 m, the surface offset is 1.2 m, and the maximum scarp angle is 21.5^{o}. Two scarps are apparent on profile NB-P2. The lower (southwest) scarp ties to the scarp profiled by NB-P1 and is interpreted as a tectonic scarp. The upper (northeast) scarp coincides with the contact between units Qa3b and Qa3a and is non-tectonic. The tectonic scarp in profile NB-P is 10.6 m high, the surface offset is 9.5 m, and the maximum scarp angle is 30.5^{o}. Unit Qa1b is probably late Holocene. Unit Qa1a, which has a surface that is 1 to 2 m higher than the creek, also is inferred to be Holocene, but it is older than unit Qa1a, perhaps middle or early Holocene (5-10 ka). Units Qa3a and Qa3b may be equivalent to deposits of the Bull Lake glaciation, based on the height of the scarp in unit Qa3b.

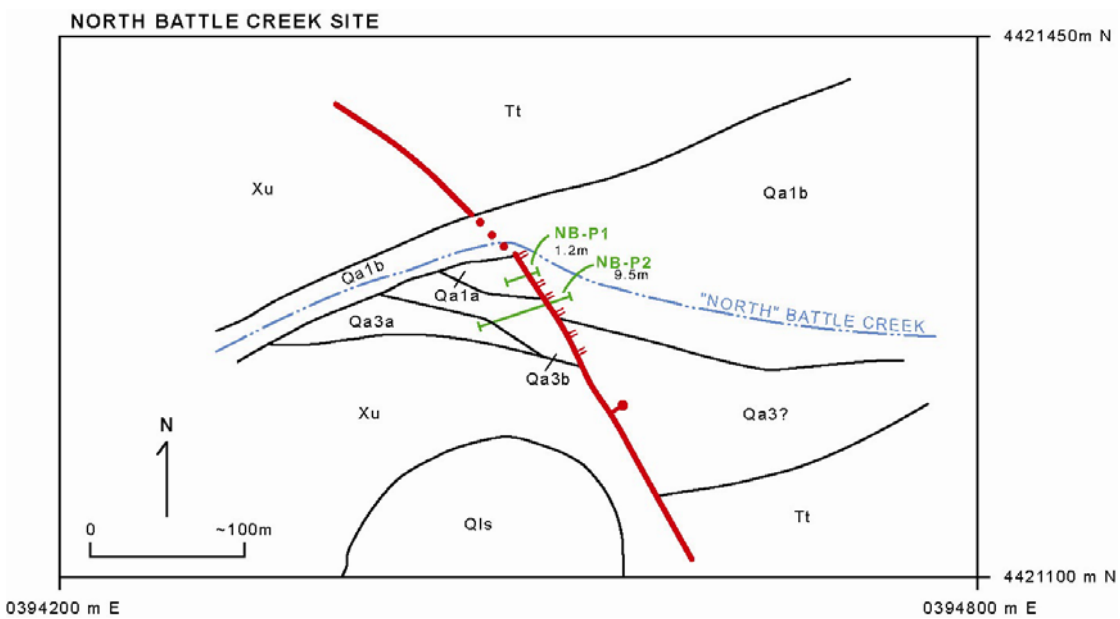

Figure 25. Geologic sketch map of North Battle Creek site. Refer to Figure 4 for location of site and Figure 6 for explanation of symbols.

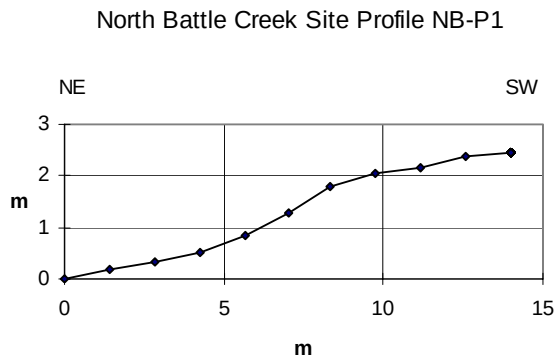

Figure 26. Profile NB-P1, North Battle Creek site. Vertical exaggeration is ~2x; scarp height = 1.4 m; surface offset = 1.2 m; θs = 21.5^{o}. See Figure 25 for location of profile.

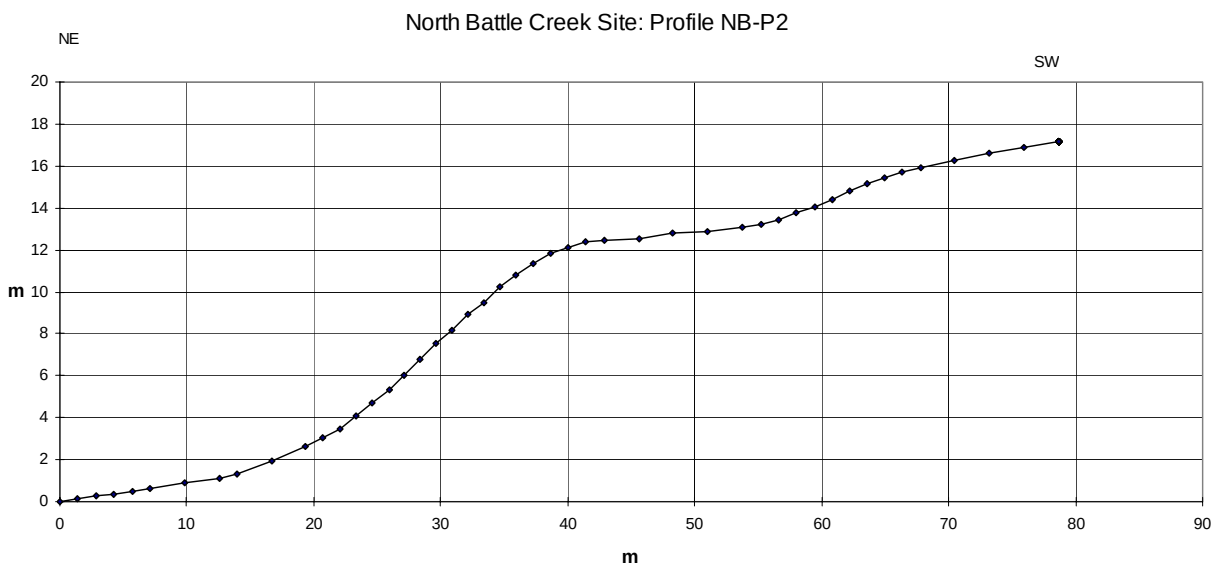

Figure 27. Profile NB-P2, North Battle Creek site. Vertical exaggeration = 2x; scarp height = 10.6 m; surface offset = 9.5 m; θs = 30.5^{o}. See Figure 25 for location of profile.

Bull Run Site

Bull Run site lies on the main fork of Bull Run (Fig. 4). The geology of this site is more complex than the previously described sites. Two tectonic scarps are mapped at this site (Fig. 28). The eastern scarp cuts two alluvial units on the south side of the creek and connects with a prominent fault-line scarp on the interfluve to the south. To the north, the fault is concealed by unit Qa1, the modern alluvium along Bull Run. The fault appears to displace unit Qa3, but erosion by a gully present at the base of the scarp has modified the scarp. Further north, this fault merges with the western scarp and becomes the main range-front scarp. The western scarp is prominent in unit Qa3 on the north side of the creek. It is on strike with the range-front fault to the south and north of the site, but cannot be confidently traced to those locations. To the south, the scarp is not present in units Qa1 or Qa2. To the north, it is concealed by young fan alluvium, and then projects to an irregular slope break that lacks a discernable fault-line scarp. It is possible that the western scarp does not have a tectonic origin.

Large boulders of vesicular basalt crop out on the scarp face south of profile BR-P1 and also on the creek bank cut into unit Qa3 on the upstream side of the scarp north of the creek. The source of this material is unknown; previous mapping in the area (Tweto and Reed, 1973; Tweto, 1973, 1978) does not show any basaltic volcanic rocks on the east side of the crest of the Williams Fork Mountains. The boulders may be eroded from unknown locations in the headwaters of Bull Run; the large size of the boulders suggests minimal transport distance. The boulders also could be from a volcanic vent in or near the fault zone.

Two profiles were measured at the Bull Run site. Profile BR-P1 (Fig. 29) is in unit Qa2 on the south side of the creek. The scarp is 8.9 m high, the surface offset is 6.6 m, and the maximum scarp angle is 23.5^{o}. Profile BR-P2 (Fig. 30) extends across the scarp in unit Qa3 on the north side of the creek. This scarp is 3.8 m high, with a surface offset of 3.4 m and maximum slope angle of 23.5^{o}. A veneer of fan alluvium from a tributary valley is present on the downthrown side of the scarp at profile BR-P2, therefore the reported surface offset may represent a minimum value. Two soil pits were excavated at the Bull Run site, one in unit Qa2 on the south side of the creek and a second in unit Qa3 on the north side of the creek. Soil samples were collected from these pits, but the grant contained insufficient funds to run grain-size analyses on the samples.

Unit Qa1 probably is Holocene. Unit Qa2 is inferred to correlate with deposits from the late Pleistocene Pinedale glaciation, and unit Qa3 may be equivalent to late middle Pleistocene Bull Lake deposits.

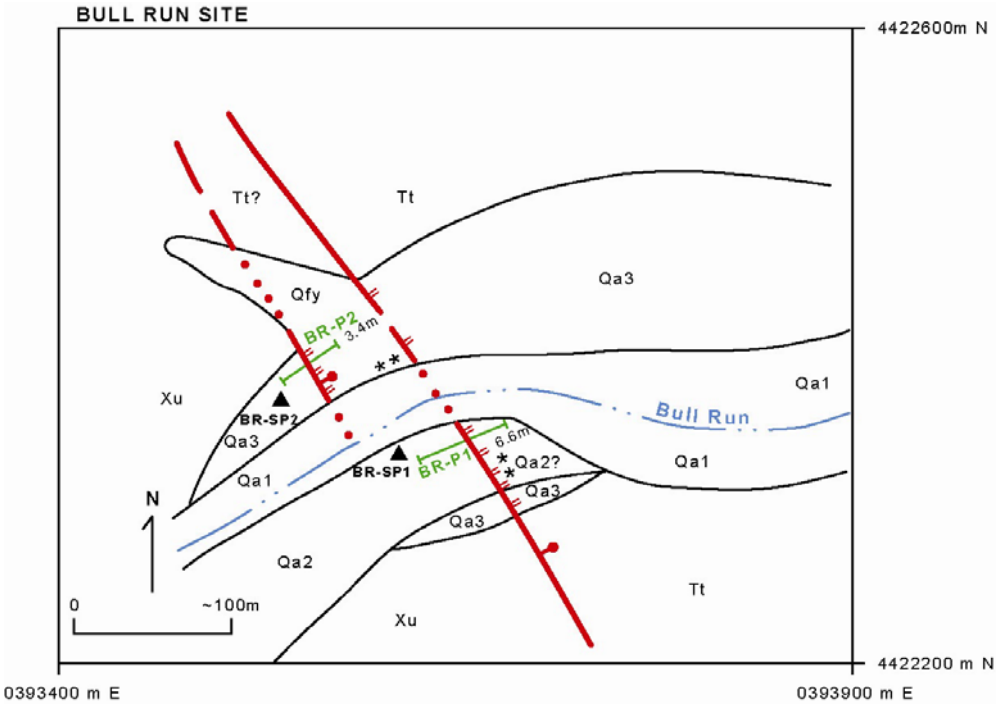

Figure 28. Geologic sketch map of Bull Run site. Refer to Figure 4 for location of site and Figure 6 for explanation of symbols.

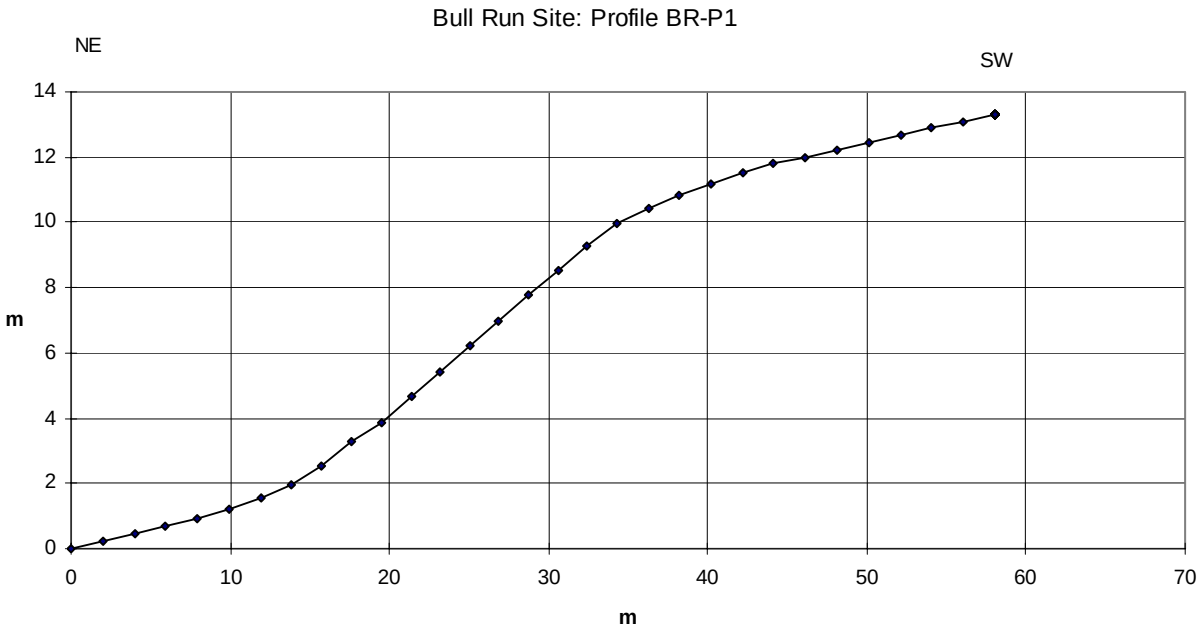

Figure 29. Profile BR-P1, Bull Run site. Vertical exaggeration is ~2x; scarp height = 8.9 m; surface offset = 6.6 m; θs = 23.5°. See Figure 28 for location of profile.

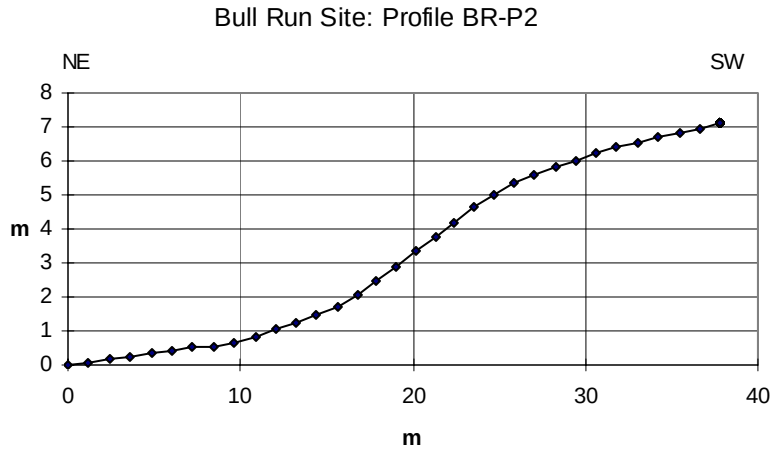

Figure 30. Profile BR-P2, Bull Run site. Vertical exaggeration is ~2x; scarp height = 3.8 m; surface offset = 3.4 m; θs = 23.5^{o}. See Figure 28 for location of profile.

Johnson Gulch Site

The Johnson Gulch site lies along the main fork of Johnson Gulch (Fig. 4). A single fault scarp is present in alluvial deposits on both sides of the creek (Fig. 31). The faulted deposit on the north side of the creek is unit Qa2. The faulted deposit on the south side of the creek (unit Qa2?) is tentatively correlated with the faulted deposit on the north side of the creek, even though the geomorphic surface on the north side of the creek is 1 to 2 m higher than the surface on the south side of the creek. Recent alluvium (unit Qa1) conceals the fault and is present on the downstream side of the fault where scarps cut units Qa2 and Qa2?. On the north side of the creek, unit Qa2 is mantled by a thin veneer of colluvium or slopewash eroded from the adjacent bedrock hillslope. This may explain why the surface on unit Qa2? on the south side of the creek is slightly lower in elevation than the surface on unit Qa2 north of the creek. The deposit of Qa2 on the south side of the creek could also be slightly younger than the deposit on the north side of the creek, which also could account for the elevation difference. The creek has cut about 6 to 8 m into unit Qa2 on the upthrown side of the fault, whereas it has incised only 0.3-0.6 m into unit Qa1 on the downthrown side.

The scarp on the south side of the creek has been disturbed by human activities, but north of the creek the scarp is intact. Profile JG-P1 (Fig. 32) was measured on the scarp on the north side of the creek. Here, the scarp height is 5.0 m, the surface offset is 3.8 m, and the maximum scarp angle is 24.0^{o}.

A soil pit was dug into unit Qa2 on the north side of the creek (Fig. 33). The upper 85 cm of the material in the pit was colluvium or slopewash derived from the adjacent hillslope, and consisted of well-sorted, sandy, small pebble gravel with angular clasts. The soil profile in this deposit included an A, AE, C1ox, and C2ox horizons. The lower 65 cm of material in the pit included 42 cm of sandy, gravelly alluvium with 2Eb?/2Bb/3Cox horizons, underlain by 23 cm of clayey, silty sand and sandy, clayey silt that perhaps included B horizons formed in loess. The

upper soil (0-85 cm) is interpreted as a Holocene soil. The 2Bb horizon at a depth of 90 to 117 cm contained 12.3 to 13.8% fine clay, significantly more than the overlying 2Eb? horizon (5.2% fine clay) and underlying 3Cox horizon (5.1% fine clay). This 2Bb horizon contains more fine clay than any other B horizon encountered during the project. If this fine clay is pedogenic, then this unit is the oldest unit exposed in the four soil pits. We estimate the age of this soil to be early Pinedale (~30-35 ka). Age estimations based on comparison of the amounts of stream incision in the faulted deposits at Johnson Gulch with those found at other sites further south along the fault is tenuous. The drainage basin above the Johnson Gulch site is much smaller in areal extent and lower in altitude than the drainage basins above sites to the south.

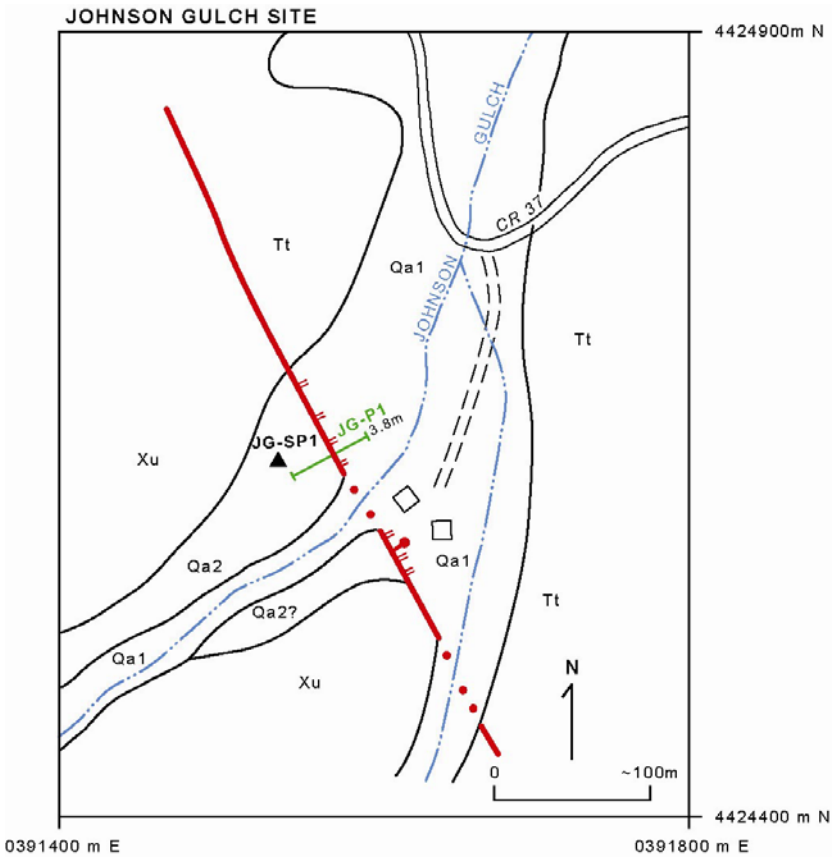

Figure 31. Geologic sketch map of Johnson Gulch site. Refer to Figure 4 for location of site and Figure 6 for explanation of symbols.

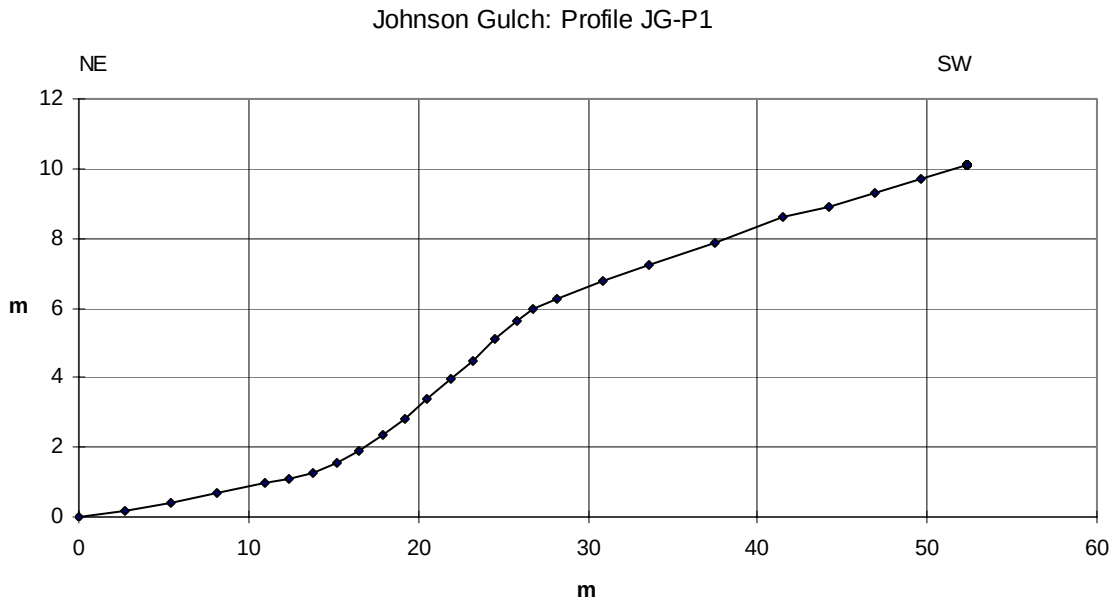

Figure 32. Profile JG-P1, Johnson Gulch site. Vertical exaggeration is ~2x; scarp height = 5.0 m; surface offset = 3.8 m; θs = 24.0°. See Figure 31 for location of profile.

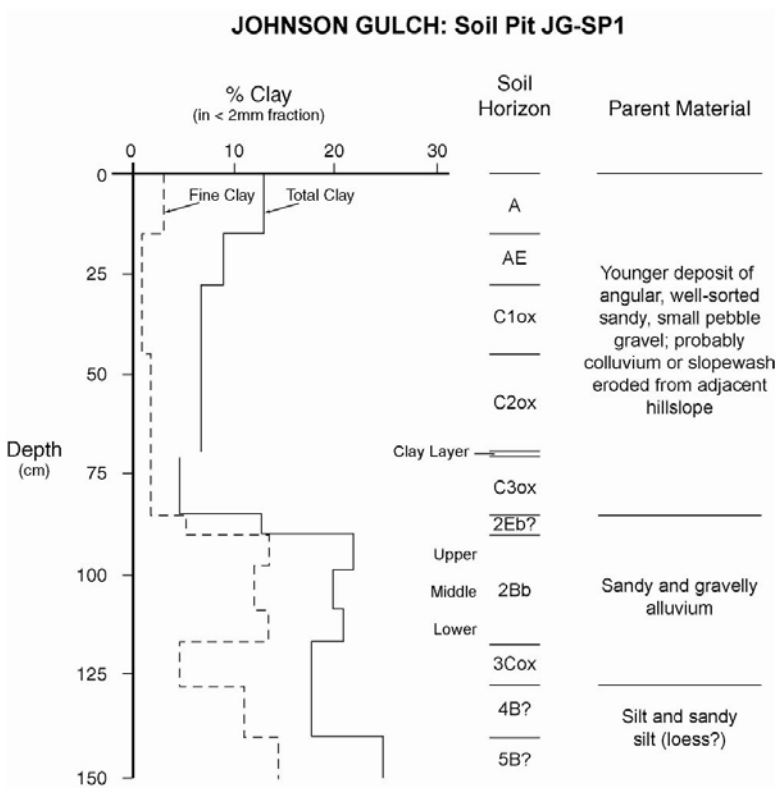

Figure 33. Pedogenic soil profiles, clay content of soil horizons, and parent material in soil pit JG-SP1 at Johnson Gulch site. See Figure 31 for location of soil pit.

North Johnson Gulch Site

The North Johnson Gulch site is situated on the northern fork of Johnson Gulch (Fig. 4). Two scarps interpreted as tectonic features are present (Fig. 34). Both scarps cut alluvial unit Qa2? on the north side of the gulch, and both are concealed by unit Qa1. To the north, the lower or easterly of the two scarps ties with the base of a prominent fault-line scarp on the interfluve. The upper or westerly scarp projects to the upper part of the fault-line scarp. South of the gulch, the two scarps appear to merge with a prominent fault-line scarp that continues to the Johnson Gulch site. Several springs issue from the fault-line scarps in this area. The gulch has eroded about 4.6 m into unit Qa2? immediately above the scarp; further upstream the incision is less, being only about 2 to 3 m. Below the scarp the gulch is on grade with the surface of unit Qa1.

This site is probably the same site reported by Unruh and others (1993, 1996), but the exact location of the site was not pinpointed in their reports. According to field books used during their earlier study, the site is situated in a tributary to Johnson Gulch (Jeffery Unruh, 2002, personal commun.). There are two sites with fault scarps in the tributaries of Johnson Gulch. The geology described by Unruh and others (1993, 1996) better matches the Johnson Gulch site than the North Johnson Gulch site. Unruh and others interpreted the lower or easterly scarp as a landslide feature. We believe the scarp is more likely a tectonic feature because (1) it directly connects with a fault-line scarp to the north, (2) there are no obvious landslide deposits below the scarp, (3) the scarp is linear, not arcuate, and (4) the scarp does not bend downstream where it approaches the valley wall, as one would expect a landslide scarp to behave.

Two profiles were measured at this site. Profile NJ-P1 crosses the lower (easterly) scarp in unit Qa2? (Fig. 35). This scarp is 5.7 m high, offsets the surface of unit Qa2? about 4.4 m, and has a maximum scarp angle of 25.0^{o}. A second profile, NJ-P2 (Fig. 36), was measured across both the upper and lower scarps. Profile NJ-P2 crossed the upper scarp at a location where the upper scarp is well preserved (see central part of profile). Profile NJ-P2 also extended across the lower scarp, but this location is next to the gulch, where fluvial erosion had degraded the scarp (left side of profile from horizontal distance 20-30 m). The combined height of both scarps along Profile NJ-P2 is 12.2 m, the surface offset is 7.7 m, and the maximum scarp angle is 23.0^{o}. Unruh and others (1993, 1996) reported that the vertical displacement on just the upper scarp at this site was about 13 m. The difference between their vertical displacement and the surface offset reported by us relates at least in part to the methodology used to calculate the value. Unruh and others projected the slope of the surface below the scarp to the preserved upper surface. Since the slope of the lower surface was less than the slope of the upper surface, this method would overestimate the surface offset.

Unit Qa1, which post-dates the last fault rupture, probably is Holocene. The age of unit Qa2? is uncertain. It may be late Pleistocene and possibly correlates with early Pinedale deposits (~30-35 ka). The unit also could be as old as other Bull Lake deposits in the region (140 to 150 ka, Pierce and others, 1976; Pierce, 1979; or 130 to 350 ka, Richmond, 1986). The drainage basin above the North Johnson Gulch site is similar in size and altitude to that above the Johnson Gulch site, so relative age estimates based on amounts of stream incision between these two sites may be appropriate. Based on the depths of incision, unit Qa2? at the North Johnson Gulch site may be slightly younger than unit Qa2? at the Johnson Gulch site. It is probably inappropriate to use the

incision data for relative dating purposes when comparing the North Johnson Gulch site to sites south of the Johnson Gulch site because of the significant differences in their drainage basins.

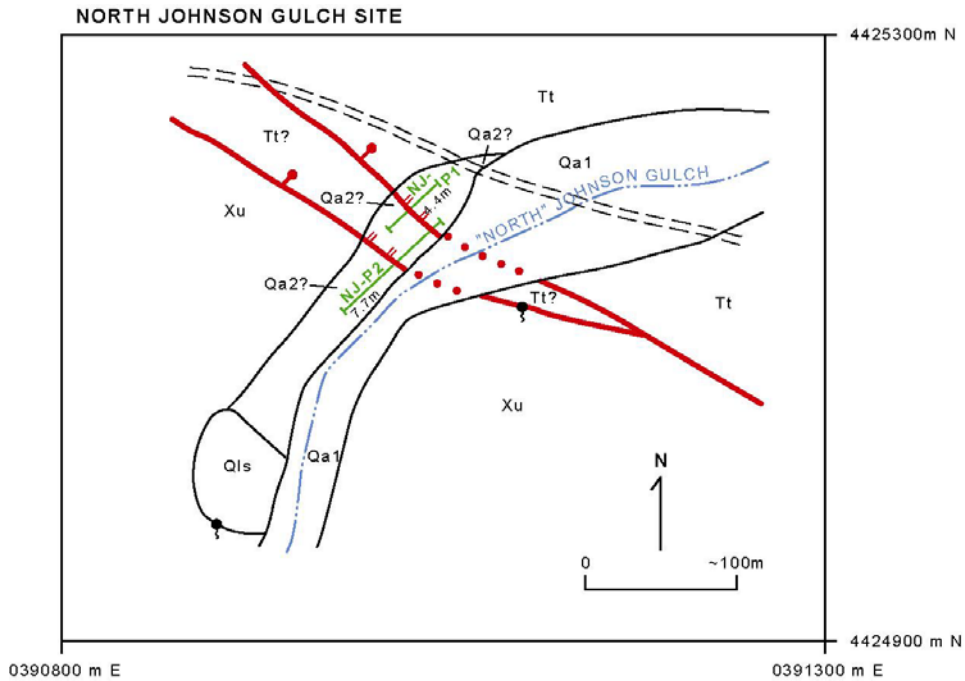

Figure 34. Geologic sketch map of North Johnson Gulch site. Refer to Figure 4 for location of site and Figure 6 for explanation of symbols.

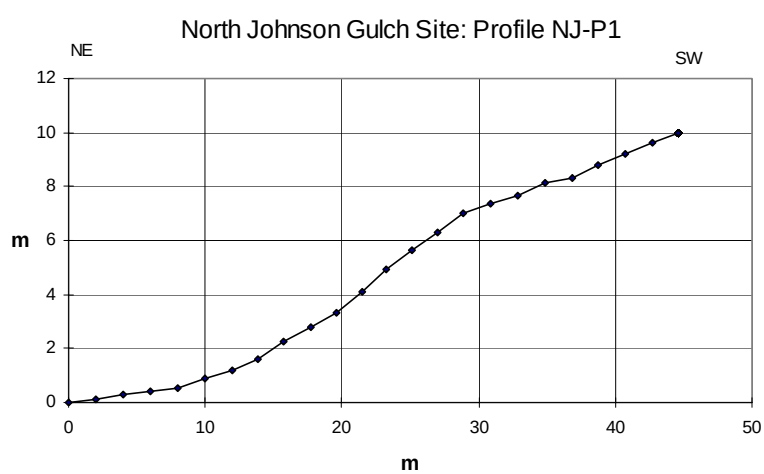

Figure 35. Profile NJ-P1, North Johnson Gulch site. Vertical exaggeration is ~2x; scarp height = 5.7 m; surface offset = 4.4 m; θs = 25.0°. See Figure 34 for location of profile.

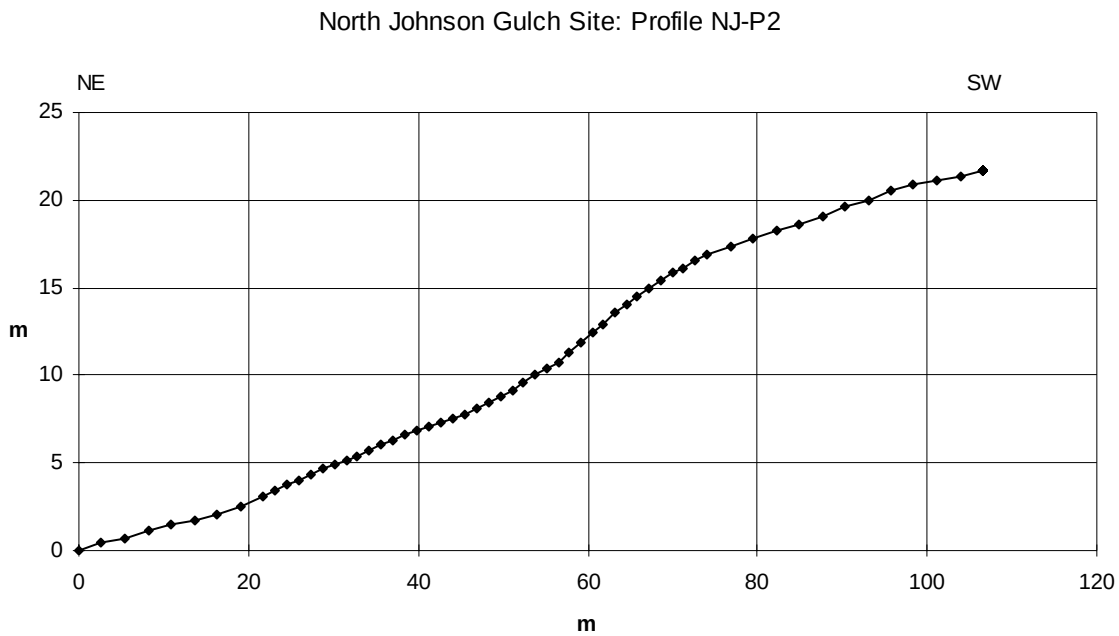

Figure 36. Profile NJ-P2, North Johnson Gulch site. Vertical exaggeration is ~2x; scarp height = 12.2 m; surface offset = 7.7 m; θs = 23.0^{o}. See Figure 34 for location of profile.

McQueary Gulch Site

McQueary Gulch site is located near the headwaters of McQueary Gulch at the northern end of the Wiliams Fork Mountains (Fig. 4). Two scarps inferred to be of tectonic origin are present at the site (Fig. 37). Both scarps cut deposits of unit Qa2?, and both are concealed by unit Qa1. Both scarps also tie with the broad fault-line scarp in bedrock west-northwest of the site. To the south, the upper scarp connects with a fault-line scarp in bedrock, and the lower scarp projects to a saddle on the ridge that is formed in the Troublesome Formation.

Two profiles were measured across the scarps at the McQueary Gulch site. Profile MG-P1 (Fig. 38) is on the lower scarp, and profile MG-P2 (Fig. 39) is on the upper scarp. The lower scarp is 4.8 m high, and has a surface offset of 3.5 m. The maximum scarp angle is 22.0^{o}. Profile irregularities on the upthrown side of the scarp (~40 m from beginning of profile) reflect human disturbances related to the jeep road. Height of the upper scarp is 10.2 m, the surface offset is 5.8 m, and the maximum scarp angle is 19.5^{o}.

Unit Qa1, which conceals the fault, probably is Holocene. Essentially no age control is available for the faulted unit Qa2?. We assign a late Pleistocene age to unit Qa2?, but realize this interpretation may be incorrect. The deposit may be as old as the Bull Lake glaciation. Since the

site lies near the headwaters of the drainage basin, the incision rates of this minor tributary probably are not similar to the incision rates at any of the other sites, and are not useful for estimating relative ages.

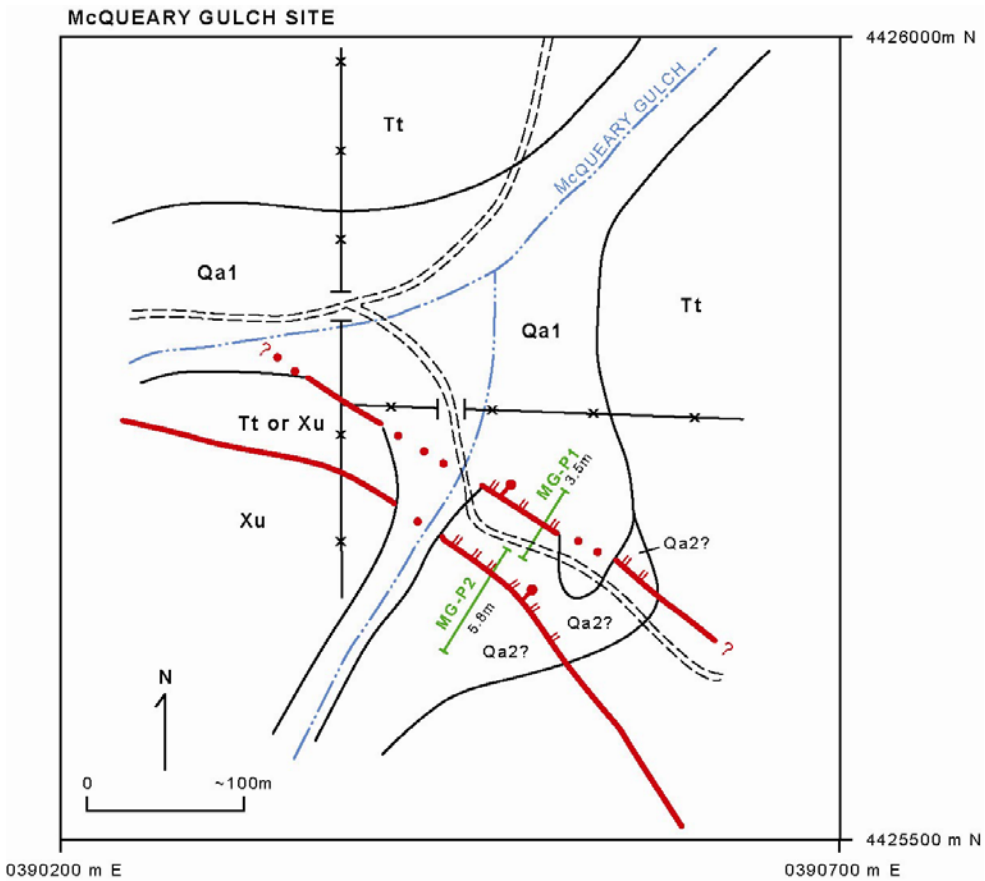

Figure 37. Geologic sketch map of McQueary Gulch site. Refer to Figure 4 for location of site and Figure 6 for explanation of symbols.

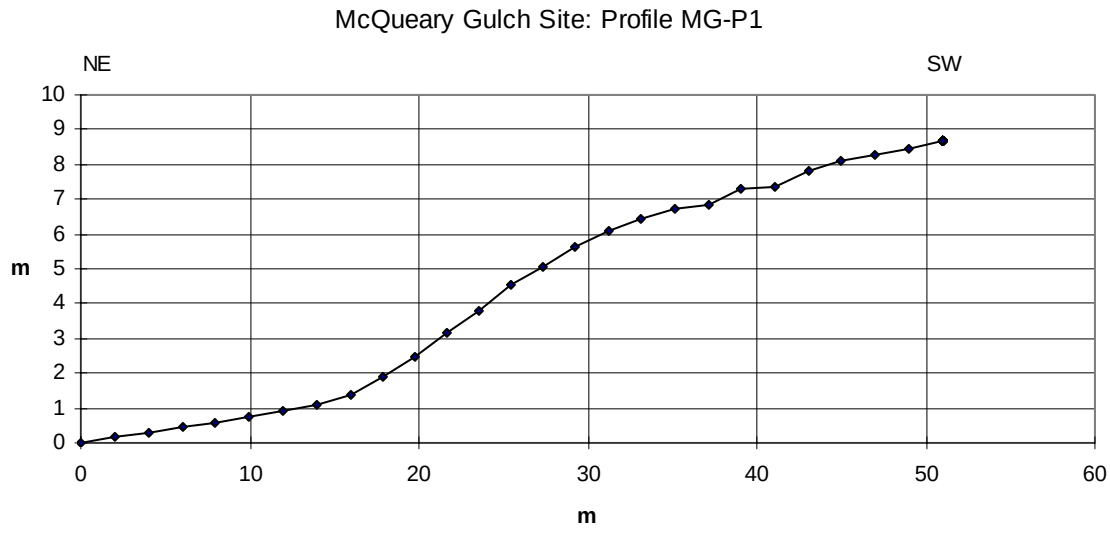

Figure 38. Profile MG-P1, McQueary Gulch site. Vertical exaggeration is ~2x; scarp height = 4.0 m; surface offset = 3.5 m; θs = 22.0°. See Figure 37 for location of profile.

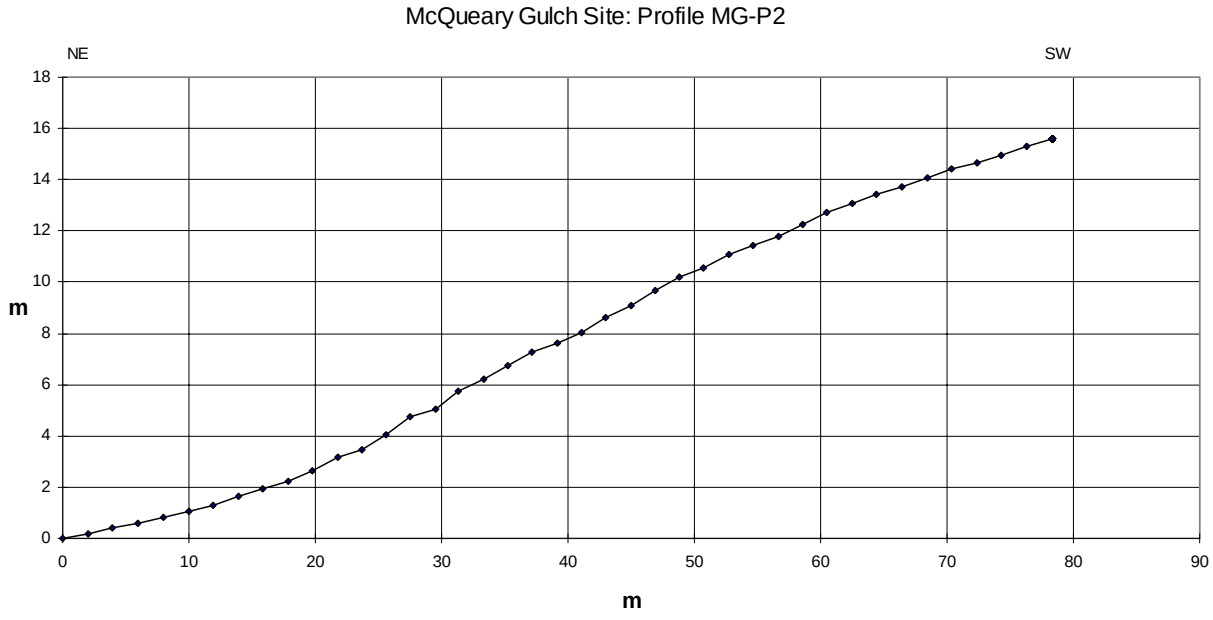

Figure 39. Profile LC-P2, McQueary Gulch site. Vertical exaggeration is ~2x; scarp height = 11.8 m; surface offset = 5.8 m; θs = 19.5°. See Figure 37 for location of profile.

Slip Rate of Williams Fork Mountains Fault

The slip rates for the Williams Fork Mountain fault reported below should be used with caution. The ages of the faulted deposits and the length and timing of the seismic cycles are poorly constrained. Scarps that cut the youngest deposits may be single-event scarps; the seismic cycle for these scarps are open ended. Nonetheless, the data collected during this investigation greatly increases our understanding of the seismogenic history of the Williams Fork Mountains fault.

The best available slip-rate estimates are from sites where soil pits provide age control for the faulted deposits. At the Lost Creek site, a unit correlated with deposits of the late Pleistocene Pinedale glaciation (12-35 ka) is offset 2.0 m, yielding a slip rate of 0.057 to 0.11 mm/year. A probable Holocene deposit at this site is offset 1.1 m. Assuming an age of 5-10 ka for the faulted Holocene unit, the slip rate ranges from 0.11 to 0.22 mm/year. These values should be considered a maximum rate for the fault at this location, because the scarp is probably the result of a single event. The Lost Creek site is near the southern end of the documented extent of late Quaternary faulting, and the slip rate may not represent the maximum or even average rate for the overall structure.

Deposits of three different ages are cut by the fault at the Middle Mule Creek site. Soil pits were excavated into the oldest and youngest faulted deposits at this site. The oldest unit, which is offset 4.3 m, probably was deposited during the Pinedale glaciation. The calculated slip rate for this scarp ranges from 0.12 to 0.36 mm/year. The youngest faulted deposit at the Middle Mule Creek site is probably early Holocene (~10 ka) or latest Pinedale (~12 ka). With a surface offset of 2.1 m, this scarp yields slip rates of 0.18 to 0.21 mm/year. The intermediate-age faulted unit at this site was inferred to be a Pinedale deposit and has a surface offset of 3.4 m. Slip rates for this scarp range from 0.10 to 0.28 mm/year.

A scarp at the Johnson Gulch site cuts a unit correlated with deposits of the early Pinedale glaciation and is estimated to be 30 to 35 ka. The slip rate of this scarp, which offsets the surface of the deposit 3.8 m, is about 0.11 to 0.13 mm/year. The Johnson Gulch site is near the northern end of known late Quaternary faulting on the Williams Fork Mountains fault.

Estimates of slip rates at the eight other sites range from a low of 0.017 mm/year at the Skylark Creek site to a high of 0.78 mm/year at the McQueary Gulch site. Most estimates at sites that lack soil pits range from about 0.10 to 0.30 mm/ year, which matches the estimates from sites with soils data fairly well.

Faults on East Side of Williams Fork Valley Graben

Several prior investigations described a system of unnamed faults that form the eastern margin of the Williams Fork Valley graben (Tweto and Reed, 1973; Tweto and others, 1976; Tweto, 1976; Kirkham and Rogers, 1981; Unruh and others, 1993, 1996; Widmann and others, 2002). In these investigations, the faults on the eastern side of the graben reportedly cut the Miocene Troublesome Formation but not Quaternary deposits. These structures were evaluated during this project using aerial photography, satellite imagery, and digital elevation models,

accompanied by limited field reconnaissance at a few sites where the structures crossed late and middle Quaternary surficial deposits. No evidence of late Quaternary tectonism was discovered on these structures on the east side of the graben. An area worthy of additional study is north of Ute Park, where the mapped trace of one of the faults on the east side of the graben crosses hills that may be underlain by middle to early? Pleistocene alluvial deposits (Fig. 4). This site was not investigated in the field during this study.

Faults within Interior of Graben

Several northeast- and north-striking Quaternary normal faults underlie the larger tributary valleys to the Williams Fork of the Colorado River, including Lost, Mule, Skylark, and Battle creeks (Fig. 4). Tweto and Reed (1973), Tweto and others (1976), and Unruh and others (1993, 1996) mapped and/or described many of these structures, which include the Lost Creek fault, Mule Creek fault, Skylark Creek fault, and Battle Mountain fault. Subsurface data acquired during a geotechnical investigation of a proposed dam site on Lost Creek (Woodward-Clyde Consultants, 1981) supports the presence of the Lost Creek fault. Sediments of the Troublesome Formation encountered in boreholes and groundwater levels were “dissimilar” across the Lost Creek fault.

Middle and possibly early Quaternary outwash gravels that were deposited by the Williams Fork cap several mesas and hilltops within the graben. The gravels are deformed by these Quaternary faults. Most cross faults are downdropped to the northwest. Many of the blocks between the faults are tilted to the southeast or east, forming a series of small half grabens or tilted fault blocks that trend to the northeast or north obliquely across the larger Williams Fork Valley graben. These faults are relatively short in length; the longest is about 8.5 km long. However, the vertical displacement of geomorphic surfaces is appreciable. The Skylark Creek fault displaces a geomorphic surface as much as 36 m.

The gravel-capped blocks are also downdropped relative to one another, with the blocks lowering in elevation from southeast to northwest as they approach the Williams Fork Mountains fault. This relationship discounts the possibility that the progressively lowered surfaces comprise a sequence of inset outwash terraces. If the downdropped surfaces were part of a flight of outwash terraces, then the Williams Fork river must have gradually migrated northwestward across the valley. However, the river now flows along the eastern edge of the tilted terraces. If the river deposited the terraces, the river must have abandoned its channel in a hypothetical paleovalley on the west side of the valley and re-established a course along the east side of the valley during the late Quaternary. It is unlikely that the river behaved in such a manner, as the river now flows in a valley cut into Proterozoic rocks along the east side of the valley for much of its length.

No scarps were observed in Holocene or late Pleistocene alluvium along the faults, but the tilting and differential offset of the mesas and hilltops capped by middle and early? Quaternary gravel indicates post-middle Quaternary deformation. The absence of scarps in late Quaternary deposits is not surprising, because the creeks flow along the faults. Fluvial erosion and deposition has altered the fault scarps into curvilinear fault-line scarps and obscured the tectonic geomorphology of the faults.

East- and northeast-striking linear valleys along minor tributaries occur within the Williams Fork Valley graben and are probably controlled by minor Quaternary faults. These linear drainages are eroded into middle and late Quaternary deposits and the underlying Miocene Troublesome Formation. Many of the linear valleys abruptly terminate against cross faults like the Skylark and Mule Creek faults. In an area between the confluence of Lost Creek and the Williams Fork, the linear drainages are aligned with saddles and faceted ridges formed in Proterozoic rocks. These landforms, which are developed in hard, resistant bedrock, may result from differential erosion along faults and hence be fault-line scarps. They support an interpretation that the shallow linear drainages resulted from post-middle Quaternary tectonism within the central part of the Williams Fork Valley graben.

Unruh and others (1993, 1996) proposed that the Skylark Creek fault forms the southern structural boundary of the Williams Fork Valley graben during both the Neogene and the Quaternary, and that the Skylark Creek fault serves as an accommodation structure for the Williams Fork Mountains fault. The tectonic model presented by Unruh and others offers several interesting concepts, but has some limitations. Quaternary deformation extends southward at least to the Lost Creek fault, and Miocene Troublesome Formation sediments are preserved at least as far south as Ute Park. This indicates the Quaternary deformation and Neogene deformation related to the graben continues southward at least to those locations. There are several post-middle Quaternary faults that strike obliquely across the graben, forming a series of subparallel tilted fault blocks. The stress transfer from the south end of the Williams Fork Mountains fault is probably accommodated by all of the Quaternary cross faults that obliquely cut across the Williams Fork Valley graben.

CONCLUSIONS

Pervasive strong evidence of late Quaternary faulting is present for about 18 km along the northern section of the Williams Fork Mountain fault. This evidence confirms that the Holocene rupture reported by Unruh and others (1993, 1996), based on their work at a single site on the north end of the fault, extends across a significant length of the fault. No evidence of late Quaternary deformation was documented on the southern section of the Williams Fork Mountains fault, which is at least 18 km long (Tweto and others, 1978). The southern section of the fault also may be active, but here the fault lies in Proterozoic rocks and rarely crosses middle to late Pleistocene deposits that could be used to judge the recent activity of the fault.

Tectonic fault scarps are present in Holocene and late Pleistocene alluvium in many of the tributary valleys that cross the northern section of the Williams Fork Mountain fault. At two sites, the Holocene deposits are offset over 1 m. At a third site a scarp displaces deposits thought to be early Holocene or latest Pleistocene over 2 m. Surface offsets of 2 to 4 m are typical in deposits tentatively correlated with the late Pleistocene Pinedale glaciation. The greatest measured surface offset of 9.5 m was in a deposit that may be age equivalent with the Bull Lake glaciation.

Ages of the faulted deposits are poorly constrained; no datable organic materials were recovered in the six soil pits. Our estimates of the ages of the faulted deposits are based on soils

data from the pits, clast weathering, and geomorphic relationships between the deposits. Additional studies are required to better establish the chronologic framework of the faulted deposits. Available data suggest the slip rate for the northern section of the Williams Fork Mountains fault is 0.1 to 0.3 mm/year.

The fault scarps along the Williams Fork Mountains fault are not gravitational-spreading features like those described by Varnes and others (1989) in the southern Williams Fork Mountains. The sackungen documented by Varnes and others occur at and near the range crest, and many are uphill facing. The tectonic scarps along the Williams Fork Mountains fault lie at the base of the range, and all are downthrown to the valley.

Several northeast- and north-striking Quaternary normal faults cut obliquely across the interior of the Williams Fork Valley graben. These cross faults offset and tilt middle and possibly early Quaternary deposits. The faults bound a series of northeast- and north-trending half grabens or tilted fault blocks that are progressively downdropped to the northwest, towards the Williams Fork Mountains fault. These faults probably serve as accommodation structures related to the Williams Fork Mountains fault and collectively, along with the Williams Fork Mountains fault, form the southern boundary of the Quaternary deformation associated with the Williams Fork Valley graben.

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We thank Patricia Hesch and Craig Magwire for issuing a permit to dig soil pits on U.S. Forest Service lands. Rusty Dersch played a key role in securing the permit for the soil pits. We are grateful to the landowners and their representatives who allowed us to work on or to cross their land. They include Erich Bower and Carl Wood with Climax Molybdenum Company, Milton Watt, Fred and Mary Woods, Ken and Lisa Rodger, Kelley and Shawn Farrell, Hugh and Pat McClearn, Terry and Carlie Barnhart, Mike Miniat, Steve Roderick, and others.

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Appendix A. Grain-size analyses of soil horizons exposed in soil pits. (analyses performed by Colorado State University Soil, Water and Plant Testing Laboratory)

Lost Creek Site: Soil Pit LC-SP1

Horizon	Depth (cm)	% Gravel (of total)	% of <2 mm fraction				
			% Sand	% Silt	% 2 μm	% 0.2 μm	Total Clay
A	5	9.1	47	40	7.2	5.8	13
E	10	16.7	44	42	9.8	4.2	14
EB	15	17.9	52	34	11.6	2.4	14
Bt1	35	24.5	74	16	7.8	2.2	10
Bt2	50	41.5	75	15	8.5	1.5	10
BC	70	48.1	74	18	7.2	0.8	8
C1ox	100	36.4	75	15	8.6	1.4	10
C2ox	120	29.6	78	14	7.1	0.9	8
Bwb	140	2.4	66	20	10.8	3.2	14

Middle Mule Creek Site: Soil Pit MM-SP1

Horizon	Depth (cm)	% Gravel (of total)	% of <2 mm fraction				
			% Sand	% Silt	% 2 μm	% 0.2 μm	Total Clay
A	5	5.1	69	24	4.1	2.9	7
AE	10	15.4	71	23	4.0	2.0	6
E	17	31.3	71	22	4.5	2.5	7
Bw	30	47.6	73	19	4.9	3.1	8
Cox	60	62.5	87	8	2.9	2.1	5
Coxb1	85	11.8	89	8	1.2	1.8	3
Cn1b	90	20	95	4	1.0	<0.1	1

Middle Mule Creek Site: Soil Pit MM-SP2

Horizon	Depth (cm)	% Gravel (of total)	% of <2 mm fraction				
			% Sand	% Silt	% 2 μm	% 0.2 μm	Total Clay
A	7	<1	53	35	8.3	3.7	12
Bw	17	<1	63	24	10.1	2.9	13
Cox	23	2.3	65	25	8.0	2.0	10
Eb	43	6.9	53	34	10.6	2.4	13
Cox1b	67	9.4	81	11	6.1	1.9	8
Cox2b	100	20	81	13	4.4	1.6	6
Cn	120	4.8	79	14	4.8	2.2	7

Johnson Gulch Site: Soil Pit JG-SP1

Horizon	Depth (cm)	% Gravel (of total)	% of <2 mm fraction				
			% Sand	% Silt	% 2 μm	% 0.2 μm	Total Clay
A	15	22.7	55	32	9.7	3.3	13
AE	28	4.8	67	24	7.6	1.4	9
C1ox	45	31.9	77	16	5.5	1.5	7
C2ox	69	27.3	83	10	5.2	1.8	7
Clay	71						
C3ox	85	32.6	89	6	3.1	1.9	5
2Eb?	90	<1	59	28	7.8	5.2	13
2Bb upper	~98	5.9	55	23	8.2	13.8	22
2Bb middle	~108	7.1	59	21	7.7	12.3	20
2Bb lower	117	5.4	55	24	7.5	13.5	21
3Cox	127	58.8	81	1	12.9	5.1	18
4B?	140	<1	55	27	7.3	10.7	18
5B?	150	<1	34	41	10.6	14.4	25

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